Master thesis in Geophysics

Comparison Between Baltic Sea Surface Heights Interpolated from Tide Gauge Measurements and Modelled Baltic Sea Surface Heights

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Tiivistelmä — Referat — Abstract

The idea for this study was to unify the heights systems in the tide gauge data available from freely available sources and to make a surface interpolation of the Baltic Sea surface heights. There were some data availability problems in the south-east coast of the Baltic Proper which lead us to limit the study area to the northern Baltic Sea.

We compared the surface interpolation made for the years 2007–2016 with the NEMO-Nordic reanalysis product sea levels in order to determine if the interpolated surface could be used as an approximation of the sea surface heights in the Baltic Sea.

Correlation between the interpolated surface and the model were 0.59–0.77 depending on the location. The model sea levels had a sudden change in the overall sea levels in mid-winter 2013–2014 and also a different trend before and after this jump. We also calculated correlations separately for each year from 2007 to 2016 for three mid-basin points. The correlations were between 0.91–0.98.

We found the interpolation to be quite susceptible to errors and missing measurements, which makes it difficult to create the surface interpolation for the southern Baltic Proper with the current data availability problems. Therefore, other methods are needed in order to approximate sea levels in that area.

Avainsanat — Nyckelord — Keywords

Sea Level, Baltic Sea, Loading Effect, Surface Interpolation, NEMO-Nordic

Säilytyspaikka — Förvaringsställe — Where deposited

Muita tietoja — Övriga uppgifter — Additional information

Contents

1
Introduction

The tide gauge measurements in the Baltic Sea have a long history. First permanent tide gauges in the Baltic Sea area are from 18th century in Copenhagen, Denmark; in Kronstadt naval base in St. Petersburg, Russia; and in Stockholm, Sweden. The longest continuous tide gauge time series are from the Stockholm tide gauge starting from 1774 and continuing to today. (Ekman, 2009) There has been an effort in the European Union to ease access to publicly funded research data with open data policies and common databases. Tide gauge data among many other data products have been collected from national research institutes to an E.U. Copernicus Marine Service database.

The idea for this study came from the Finnish Geospatial Research Institute. Deformation of the earth's crust by varying surface loads has been increasingly studied. There is a growing need for geodetic measurements done in high accuracy over short time scales, where the time-varying components don't necessarily average out. In order to eliminate the environmental loading effects like the effect of atmosphere, hydrology and local sea, their mass variations need to be known. (Nordman, 2010)

1.1 Goals of the Study

For geodetic measurements in northern Europe, the Baltic Sea mass creates a variable loading effect. The idea for this study was to unify the heights systems in the tide gauge data sets and to make a surface interpolation of the Baltic Sea surface heights from the tide gauge data for the purpose of evaluating the mass variability of the Baltic Sea.

In this study, a surface interpolation from the tide gauge measurements in the northern Baltic Sea area was made. This surface was then compared with the modelled sea level heights from NEMO-Nordic reanalysis product in order to determine if an interpolated surface from tide gauge sea levels could be a used as an approximation of the sea surface heights in the Baltic Sea?

In chapter 2 we discuss what influences sea level height in the Baltic Sea. In chapter 3 we discuss the tide gauge data sets used for making the surface interpolation and the NEMO-Nordic model we compared the interpolation with. We also discuss a poor areal and time coverage of the southeastern Baltic Proper that resulted in restricting the area of the study to the northern Baltic. In chapter 4 we discuss the steps made in order to make the surface interpolation and the comparisons with the model. Chapter 5 is presenting our findings and in chapter 6 we discuss the results, possibles errors, and give our answer to the research question we had. We also take a look at how this work could be continued further.

2
Theory

In this chapter, we discuss the different reasons behind sea level changes in the Baltic Sea. First, we take a brief look at the recent changes in the global mean sea level. Then we give some background information on the Baltic Sea in general before discussing changes in the total volume of the Baltic Sea, meteorological effects that redistribute the water, effects of other long waves, effects of density variations, and finally the effect of the land uplift in the northern Baltic Sea.

2.1 Global Mean Sea Level

Due to an increase in the global mean temperatures, changes in the global mean sea levels have been observed. Church & Gregory (2019, p. 1139) evaluates that from 1901 to 2010 there would have been 1.7 mm per year increase to the global mean sea levels and that for the period of 1993 and 2010, it would have been as high as 3.2 mm per year. Watson et al. (2015) calculates slightly lower global sea level change of 2.6 ± 0.4 – 2.9 ± 0.4 mm per year from satellite altimeter data for a period of 1993 to mid-2014 the value depending on estimations of vertical land movement used.

According to Church & Gregory (2019, p. 1139) the reasons contributing to the global sea level change is the thermal expansion of the sea water, mass loss of glaciers and ice sheets and changing freshwater storage on land. From the year 1971 75 % of the rise in the global ocean sea levels can be explained by the thermal expansion and mass loss of glaciers and ice sheets. (Church & Gregory, 2019)

2.2 Sea Level in the Baltic Sea

2.2.1 About the Baltic Sea

Baltic sea is a shallow intra-continental sea with an area of 392,978 km^2, an average depth of 54 meters and a maximum depth of 459 meters. Baltic Sea water is brackish with an average salinity of 7 ‰. (Leppäranta & Myberg, 2009, p. 3)

Baltic Sea lies between the continental sub-artics climate on the eastern side and the moist mild maritime temperate climate of North Atlantic on the west and south-west. (Leppäranta & Myberg, 2009, p. 25). Temperatures in the Baltic Sea area have a large seasonal variation and the thermal memory of the Baltic Sea water is around 2–3 months. During winters the Baltic Sea freezes with annual ice extent 12.5–100% of total Baltic Sea area for 5–7 months. (Leppäranta & Myberg, 2009, p 14-15, 27) Winds are generally strongest between October and February. During spring and early summer from April to June, winds are weaker. (Leppäranta & Myberg, 2009, p. 39-40)

The Danish straits play an important role in the exchange of water between the North Sea and the Baltic Sea. Skagerrak is a strait in the North Sea that has a mean depth of 230 m with no sill towards the strait of Kattegat. Kattegat forms a transition zone between the North Sea and the Baltic Sea, it has a mean depth of 23 meters and a maximum depth of 130 meters. There is a strong mixing in Kattegat between the North Sea and Baltic Sea waters and the waters entering the Baltic Sea have a salinity range from 20 – 30 ‰. The Danish straits consist of the Belt Sea and Öresund. In the south of Öresund, the sill height of Drogden-Flint channel is around 8 meters. The Belt Sea is the main transport route of waters between the North Sea and the Baltic Sea, with 70-75 % of the water exchange going through there. In the south, the Belt Sea waters cross the Darss sill with a depth of 18 meters to enter south-western Baltic Sea. (Leppäranta & Myberg, 2009, p. 46-49)

2.2.2 Water Budget of the Baltic Sea and the Fill Level

Baltic Sea has a volume of 21,205 km^3. The yearly evaporation is of the order of 175 km^3 and the precipitation of the order of 215 km^3. River runoff adds approximately 440 km ^{3} freshwater per year. River discharge has a strong seasonal variation, with a maximum after the snow melt. (Leppäranta & Myberg, 2009, p. 96)

The large yearly input of fresh water creates a strong outflow of fresh low-density surface waters from the Baltic Sea towards the North Sea. On the bottom layer more saline denser North Sea waters enter the Baltic Sea. The waters go through intense mixing and entrainment of the surface waters in the Danish straits. The flow in the Danish straits is mainly driven by the sea-level difference between the Baltic Sea and the North Sea, air pressure and wind distribution. Therefore it is not a steady flow. The instances of inflow and outflow events are of magnitude greater than the mean flow and have a variable salinity between 8–28 ‰. The strength, duration and the end salinity of the inflows have intra-annual and inter-annual variations, most of the inflows being short continuously occurring events with moderate salinity and major inflows of salinity high enough to renew the near-bottom layers of Baltic Sea happening only about once a decade. (Leppäranta & Myberg, 2009, p. 60–64, 98–101).

On average the yearly inflows add up to 1,180 km^3 and yearly outflows to 1,660 km^3. The active water storage capacity, the difference between the maximum monthly mean and minimum monthly mean volumes of the Baltic Sea, is of the order of 500 km^3. (Leppäranta & Myberg, 2009, p.90, 98-101)

2.2.3 Meteorological Effects

Atmospheric pressure can have a big impact on sea levels. In a theoretical case without winds affecting the situation, a change of 1 hPa would cause a 1 cm change in the sea surface. In practice wind and atmospheric pressure differences affect the sea level simultaneously. (Lisitzin, 1974, p. 59-69)

Wind can pile up sea water, especially at the ends of bays, this causes sea level changes with periods from a day to several weeks (Leppäranta & Myberg, 2009). The accumulation or depletion of water along the coast is an effect of the tangential stress of the wind force upon the water surface. In the more extreme cases, when the effect is connected with the winds of rapidly moving storm formations, the effect on sea level is also called storm surges. Storm surges have a time span from a few hours to two or three days and are characterized by first an increase in sea level to peak and then followed by a decrease in the sea level. The effect of the pressure difference in the fast-moving storm systems don't usually have enough time to have a big impact on the sea level and the sea level change is mainly due to the wind effect. (Lisitzin, 1974, p. 69-70)

Seiches are standing waves that occur in semi-enclosed or enclosed water basins (Lisitzin, 1974). They have timescales from hours to several months in the Baltic Sea. (Leppäranta & Myberg, 2009)

2.2.4 Other Long Waves

Tsunamis resulting from earthquakes, volcano eruptions or underwater explosions can also cause long waves that can change the sea level. Earthquakes can change the sea level more permanently as they can cause the seabed to rise or subside. The vertical displacement can also affect the tide gauge measurement stations operating in the area. (Lisitzin, 1974, p. 197-203) However, the occurrence of strong earthquakes and tsunamis are extremely rare in the Baltic Sea (Leppäranta & Myberg, 2009, p. 191).

Tidal effects are caused by the small deviations of the gravitational force of the sun and the moon on the surface of the earth. The deviations arise because the gravitational force is inversely proportional to the square of the distance between the bodies that are creating the force. Water particles experience different gravitational pull towards the moon and the sun depending on the distance from them. (Lisitzin, 1974)

In smaller basins like the Baltic Sea, the gravitational differences are not strong enough to create strong tidal effects and the Baltic Sea is sheltered as an intra-continental sea from the tidal influence of the open ocean.(Leppäranta & Myberg, 2009) According to Witting (1911) most of the Baltic tidal effects account to 2–5cm variations to sea level, but from eastern Gulf of Finland greater than 10 cm have been seen (as cited by Leppäranta & Myberg, 2009)

Chandler effect or "pole tide" is a change in the mean sea level caused by changes in the rotation of the earth with a period around 14 months. Maximov and Smirnov (1964) compute the deviation to mean sea level to be between -5.4 – 4.6mm for latitude 90° N where the effect is largest (as cited by Lisitzin, 1974)

2.2.5 Effect of Density On Sea Level Variations

According to Lisitzin (1974), the effect of density variation in the Baltic Sea is not very big. Variation in the water density contributes to about 10% of the range of monthly mean values for a specific area. Along the Finnish coast, the effect would be around 2.4–3.3 cm. (Lisitzin, 1974, p. 86–90) According to Ekman & Mäkinen (1996) there is, however, a consistent difference starting from the inner part of the Gulf of Bothnia towards the south and then west to the Skakerrag amounting to a 35–40cm difference in the sea levels. This difference is resulting from the difference in the overall salinity. (Ekman & Mäkinen, 1996)

2.2.6 Land Rise

During Weichselian glaciation, the latest glacial period in northern Europe, the crust was weighted down by the mass of the Fennoscandian ice sheet. The glacial period ending and the ice melting resulted in land uplift. (Leppäranta & Myberg, 2009, p. 269-270) According to Ekman (1996), the apparent land uplift relative to sea level in the area of the Bothnian Sea would be 5–8 mm per year, in the Bay of Bothnian 7–9 mm per year, in the Gulf of Finland 0–2 mm per year, and in the northern Baltic Proper 0–4 mm per year.

3 Used Data Sets

We wanted to study the sea level variation in the Baltic Sea. To do so, we compiled a data set from freely available sources. Sea level data used in this study was downloaded from two open data archives; Copernicus Marine Environment Monitoring Service (CMEMS) and archives of Swedish Meteorological and Hydrological Institute (SMHI). We also wanted to compare the interpolated sea level surfaces with modelled sea levels. For this, we used NEMO-Nordic reanalysis data, also from CMEMS. Data in CMEMS archives are funded by the EU and is free to download and use. All figures in this thesis representing tide gauge data and modelled sea levels are "Generated using E.U. Copernicus Marine Service Information". (Copernicus Marine Environment Monitoring Service, 2018)

Sea level data used are measurements from permanent tide gauge stations on the Baltic Sea coast. In this chapter, we first take a look at how tide gauge measures the sea level. Next, we discuss the reasons, why two sources for the tide gauge data was used. Then we examine both of the tide gauge data sets in more detail and discuss briefly why we decided to narrow the analysis to the northernmost Baltic Proper, the Gulf of Finland, and the Bothnian Sea. Lastly, we take a look at the Baltic Sea physical model NEMO-Nordic reanalysis product.

3.1 Tide Gauge Time Series of the Baltic Sea Region

3.1.1 How Does a Tide Gauge Measure the Sea Level?

Tide gauges are measurement stations on the shoreline where the sea level is measured from a deep measurement well. In figure 3.1 there is a schematic of a tide gauge from the

Finnish Meteorological Institute. The measurement is done from the measurement well that is connected to the sea with a damping pipe, to ensure that waves have minimal effect on the measurement. A float connected to a counterweight with hole wire is reacting to the sea level changes inside the measurement well. Above the measurement well, encoders change the mechanical information from the float-counterweight system to digital form and this information is then stored with the recording units. Near the well, there is a height benchmark that is connected to the national leveling network. The difference of the tide gauge's leveling point to the benchmark is checked regularly to ensure the accuracy of the measurement. (Finnish Meteorological Institute, 2017b)

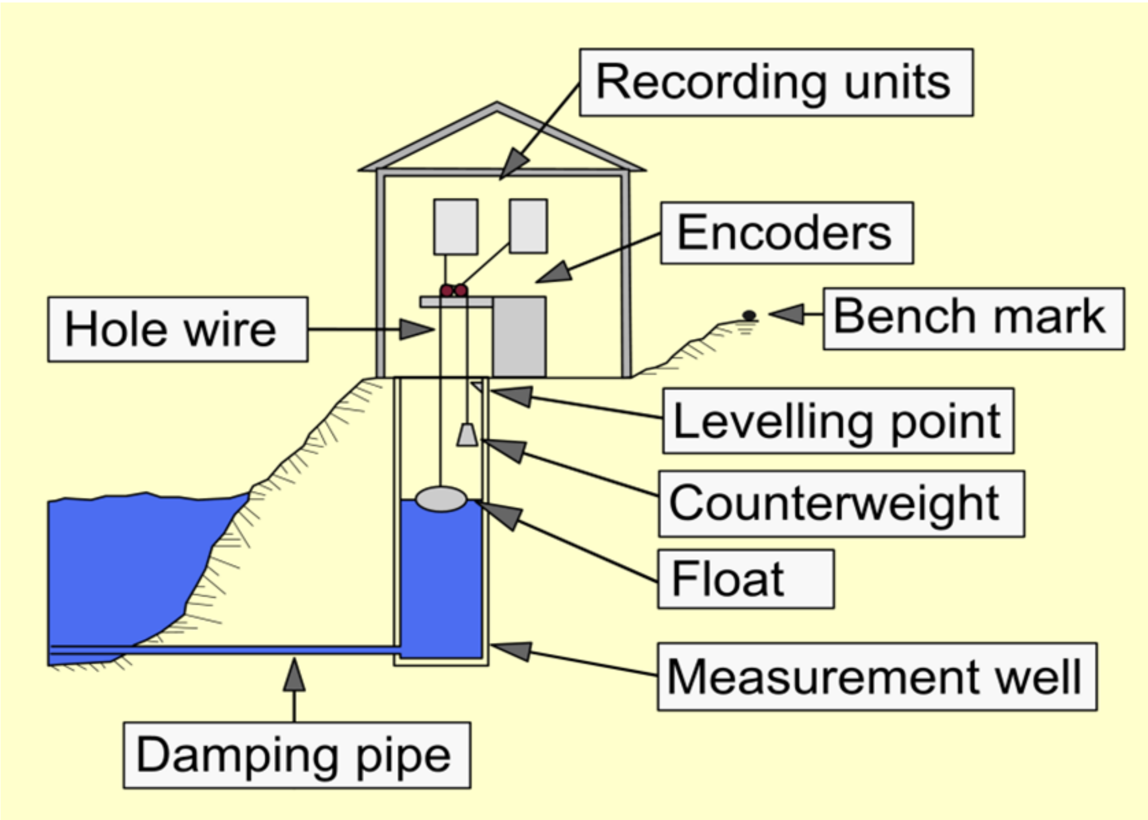


Figure 3.1: Schematics of a tide gauge from the Finnish Meteorological Institute (2017b) presented here with permission. Measurement well is connected to the sea with a damping pipe to minimize waves influence on the measurement. The float inside the measurement well rises and falls with the changing water levels and this change is then relayed with the hole wire to the encoder and recorded with the recording units. (Finnish Meteorological Institute, 2017b)

3.1.2 Mean Sea Level Height System of Tide Gauge Data for Finland and Sweden

For Sweden and Finland, the available tide gauge data in the CMEMS database is in a height system known as Mean Sea Level (MSL) or Theoretical Mean Sea Level. Sea levels in MSL height system are variations from estimated mean sea level defined for each tide gauge station yearly. The estimation of the mean includes the effects of the global sea level change, the changes in the total volume of the Baltic Sea and the land uplift. (Leppäranta & Myberg, 2009; Finnish Meteorological Institute, 2017a)

We wanted to unify the tide gauge data height systems and therefore needed the data in heights we could convert into EVRF 2007. For data from the Finnish tide gauges, a chart provided by the Finnish Meteorological Institute (2017a), was used to convert the MSL heights to current Finnish national height system N2000. For Swedish tide gauge measurements, open data resources provided by the SMHI were used instead of the data from CMEMS database, since it was available in the Swedish national height system RH2000.

3.1.3 CMEMS: Baltic Sea in Situ near Real Time Observations Data Set

Copernicus is a European Commission program for information services on satellite observations and in situ data (Copernicus program, n.d.). The Copernicus Marine Environment Monitoring Service (CMEMS) is a thematic service for the physical state, variability, and dynamics of the ocean and marine ecosystems both globally and in regional seas in Europe (Copernicus program, 2017). The data set used is the Baltic Sea in Situ near Real Time Observations. Data are quality controlled using automatic tests such as peak detection, statistical tests comparing data with climatology and neighboring measurements, and on doubtful data a visual examination by an ocean expert. Quality control flags are assigned to each measurement. Table 3.1 shows quality flags used in the data set. (Copernicus Marine environment monitoring service, n.d.)

Quality Flags
0 = No quality control was performed
1 = Good data, passed all real time quality control tests
2 = Probably good data
3 = Bad data that are potentially correctable
4 = Bad data, data has failed one or more of quality control tests
5 = Value changed, data may be recovered after transmission error
6 = Not used
7 = Nominal value, data was not observed but recorded (e.g. instrument target depth)
8 = Interpolated value, missing data may be interpolated from neighbouring data
9 = Missing value, observation was performed but is not available

Table 3.1: Quality flags used by the Copernicus Marine Environment Monitoring Service's "Baltic Sea in Situ near Real Time Observations" data set. (Carval et al., 2017, p.20)

Tide gauge data are available through the CMEMS service from 1.1.2007 to present but this has substantial variability between the tide gauge stations. In table 3.2 there is a short summary of data availability. Data from CMEMS service are in various original height systems: data from Denmark are in height system DVR90, data from Germany are either in DHHN92 or SNN76 height systems and data from Poland, Russia, Estonia, Latvia, and Lithuania are in height system BHS77. Data from Finland and Sweden are in height system referring to yearly mean sea level (MSL). The time interval between measurements varied from 5 minutes to 1 hour. Time used was UTC.

Country	Number of tide gauges	Period	Measurement interval	Height system
Denmark	27	starting from 1991 (varies by station) - current	10 min	DVR90
Germany	26	starting from 2005 (varies by station) - current	mostly 15 min	DHHN92 SNN76
Poland	1	2006-2007	10 min	BHS77
Lithuania	1	2006-2014	1 hour	BHS77
Latvia	2	2005-current	1 hour	BHS77
Estonia	14	starting from 2004 (varies by station) - current	1 hour	BHS77
Russia	3	starting from 2004 (varies by station) - current	5 min/ 15 min / 3 hour	BHS77
Finland	14	1971 - current (Porvoo from 2014)	1 hour	MSL
Sweden	30	starting from 1886 (varies by station) - current	1 hour	MSL

Table 3.2: Tide gauge data availability by country from Copernicus Baltic Sea In Situ Near Real Time Observations data sets. When tide gauge data availability varied by tide gauge station, the earliest year was used.

3.1.4 Tide Gauge Data from SMHI Open Data Service

Tide gauge data is available in SMHI Open Data Service in Swedish national reference height RH2000 and in MSL height system. We used data with RH2000 heights. A time interval between measurements were one hour and they were in UTC time. Tide gauge data were prechecked and given quality flags. Controlled and good data had a quality flag "Green". Roughly controlled, suspicious data, and mean of a sample of original data all had "Yellow" flag. Uncontrolled data had "Orange" quality flag. When combining the Swedish tide gauge data with the CMEMS data "Green" flags were translated as good data, "Orange" flags were translated as quality flag not used and "Yellow" flags were translated as bad data. (Swedish Meteorological and Hydrological Institute's Open Data Service, n.d.) SMHI's tide gauge data are free to download and use according to its open data license. (Swedish Meteorological and Hydrological Institute, 2018)

3.1.5 Poor Areal and Time Coverage of Southeastern Part of Baltic Proper

Tide gauges for available data are plotted in figure 3.2. The area around Danish straits has dense coverage of tide gauges, the northernmost Baltic Proper, Gulf of Finland and Bothnian Bay have also good areal coverage. In the CMEMS archives only two tide gauge

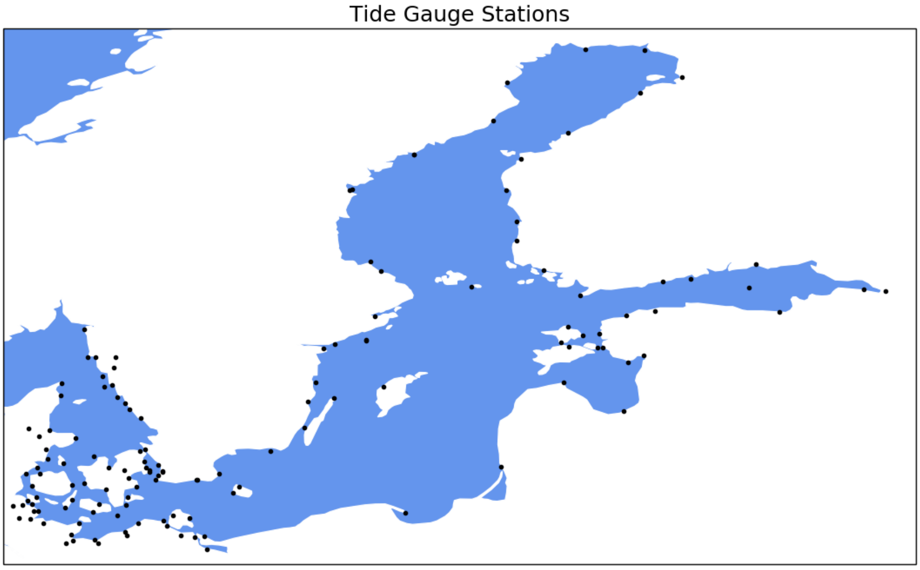


Figure 3.2: Tide gauges of Copernicus Marine Environment Monitoring Service's Baltic Sea in Situ near Real Time Observations data set. There is poor areal coverage in the southeastern part of the Baltic Proper.

stations are located in the southeastern part of the Baltic Proper, one in Poland and one in Lithuania. Table 3.1 shows that the tide gauge in Poland had data available from 2006 to 2007 and the tide gauge in Lithuania had data from 2006 to 2014. Some initial analyses were made with the whole area of the Baltic Sea, however, later the area for the analysis was cut from the latitude 58.7. The decision to focus on the northern Baltic is discussed more in chapter 4. Tide gauges in the northern Baltic are shown in figure 3.3. Due to time coverage limitation of Estonian tide gauges, the analysis concentrates on years 2007-2016.

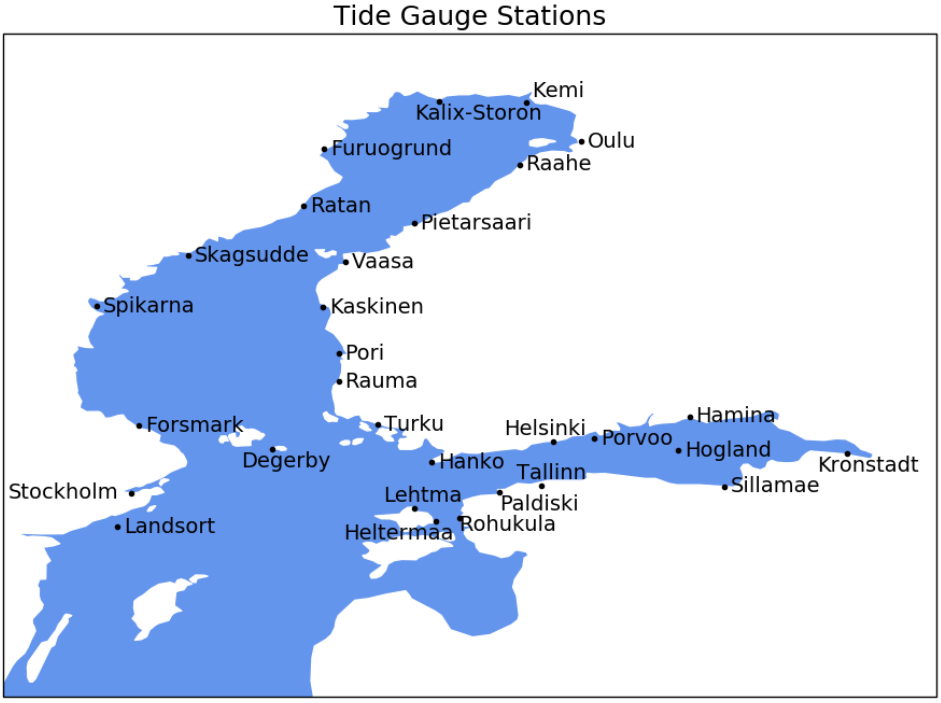


Figure 3.3: Tide gauge stations in the northernmost parts of the Baltic Proper, the Gulf of Finland and the Bothnian Bay.

3.2 CMEMS: Baltic Sea Reanalysis model

CMEMS Baltic Sea Reanalysis is a product that uses ice-ocean model NEMO-Nordic. NEMO-Nordic is based on Nucleus for European Modelling of the Ocean (NEMO) model version 3.6 and Local Singular Evolutive Interpolated Kalman filter (LSEIK) for data assimilation. Assimilated observations are sea surface temperature and profiles of temperature and salinity. The horizontal grid used is a staggered Arakawa C-grid. Horizontally the grid ranges from longitude 9 °E to 31 °E and from latitude 53 °N to 66 °N. Grid resolution is: Δ longitude = 0.05556 °and Δ latitude = 0.03333 °(approximately 4.1 km x 3.7km). With the addition to the surface layer, there are 56 native vertical layers. (Axell, 2018) The vertical resolution of NEMO-Nordic is 3 m until 60 m depth but increases towards the bottom. It uses a nonlinear free surface approach. Baroclinic modes are calculated with 360 s time steps, the barotropic time step is set to be 30 times smaller. (Hordoir et al., 2019)

NEMO-Nordic is run for the Baltic Sea and part of the North Sea, it has two open boundaries one in English channel and another between Scotland and Norway. Boundaries are described with storm surge model North Atlantic Model (NOAMOD). NEMO-Nordic is coupled with Sea Ice model Louvain-la-Neuve Sea Ice Mode (LIM) 3.6. Swedish Coastal and Ocean Biogeochemical model (SCOBI) is coupled one-way and it doesn't effect NEMO-Nordic's physical states. River runoff is given as daily means from E-HYPE (Europe HypeWeb) hydrological model. Meteorological forcing is from High Resolution Limited Area

Model (HIRLAM) with a 22 km resolution to the year 2013 and with 11 km resolution from 2014 onward. (Axell, 2018)

The online data service provides hourly data and daily and monthly means. Hourly data are available on sea surface height, ice concentration, and total ice thickness. Variables available as daily and monthly means are salinity, temperature, horizontal current components, mixed layer depth, bottom salinity, and bottom temperature. Reanalysis product is available from 1.1.1993 to 31.12.2016. (Axell, 2018)

We used hourly sea surface height from the reanalysis data set. Axell et al. (2018) estimated that the correlation of the sea level height of the reanalysis product and the CMEMS sea level stations (Denmark, Germany, and Sweden) in the Baltic Sea area for the sample year of 2015 is 0.95 and mean RMS error is approximately 7cm.

4
Methods

In this chapter, we discuss methods used in comparing the surface interpolation from tide gauge measurements to the NEMO-Nordic model reanalysis product. We also present the steps we needed to take in order to make the interpolated sea level surfaces from the tide gauge data.

First, we take a look at the preliminary work we did to the tide gauge data files. Then we discuss how we made the surface interpolation and why we ended up limiting our area to the Bay of Bothnia, the Bothnian Sea, the Gulf of Finland and the northernmost Baltic Proper. Then we examine some problems we had with the initial interpolations and what was done to minimize such problems, when new interpolation was made. Finally, we take a look on how we matched the tide gauge locations with the model grid and present the locations in the Bay of Bothnia, the Bothnian Sea and the Gulf of Finland we use in our analysis in chapter 5.

4.1 Making an Interpolated Surface from the Sea Level Data

4.1.1 Preliminary Work with Sea Level Data

While combining the tide gauge data sets from SMHI and CMEMS the SMHI data's quality flags were translated to quality flags used by CMEMS, like explained in section 3.1.4.

Tide gauge data had varying time steps. The time interval was generally from five minutes to three hours. The measurement interval by country can be seen in the table 3.2. There were irregularities with some of the tide gauge data files, where the time interval would be of varying length. To homogenize the data set, the time interval of one hour was

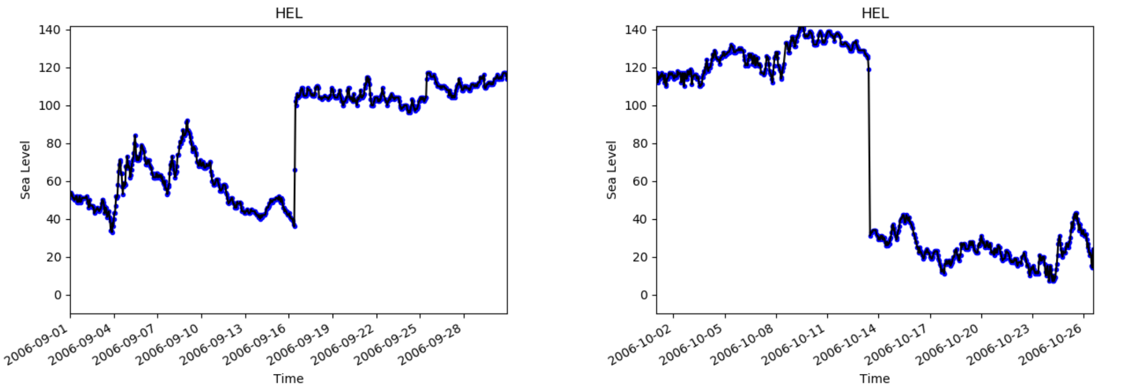
Station	**Data period**	**Usable data**	**Good data**	**Notes**
Kemi	1.1.1971 – 31.10.2018	97.4 %	97.4 %	
Kalix-Storön	1.8.1974 – 9.1.2019	99.3 %	33.0%	no qc 66.3%
Oulu	1.1.1971 – 31.10.2018	99.7%	99.7%	
Furuögrund	1.1.1916 – 9.1.2019	99.7 %	9.4 %	no qc 90.2%
Raahe	1.1.1971 – 31.10.2018	99.7%	99.7 %	
Ratan	26.10.1891 – 9.1.2019	100.0 %	64.6 %	no qc 35.4%
Pietarsaari	1.1.1971 – 31.10.2018	99.9%	99.9%	
Skagsudde	26.5.1982 – 11.7.2018	76.5%	23.8%	no qc 52.6%
Vaasa	1.1.1971 – 31.10.2018	99.9%	99.9%	
Spikarna	24.9.1968 – 9.1.2019	99.9 %	17.7%	no gc 82.2%
Kaskinen	1.1.1971 – 31.10.2018	99.5 %	99.5%	
Pori	1.1.1971 – 31.10.2018	97.7%	97.7%	
Rauma	1.1.1971 – 31.10.2018	99.9%	99.9%	
Forsmark	6.8.1975 – 9.1.2019	100.0%	20.9%	no qc 79.1%
Turku	1.1.1971 – 31.10.2018	99.9%	99.9%	
Degerby	1.1.1971 – 31.10.2018	99.9%	99.9%	
Stockholm	1.1.1889 – 9.1.2019	100.0%	8.2%	no qc 91.8%
Landsort Norra	14.10.2004 – 9.1.2019	100.0%	63.6%	no qc 36.4%
Hanko	1.1.1971 – 31.10.2018	99.9%	99.9%	
Lehtma	23.10.2006 – 31.10.2018	92.4%	92.4%	
Heltermaa	1.1.2017 – 31.10.2018	88.1%	88.1%	
Rohukula	30.11.2009 – 31.10.2018	88.1%	88.1%	
Helsinki	1.1.1971 – 31.10.2018	100.0%	100.0%	
Tallinn	14.11.2005 – 31.10.2018	92.9%	92.9%	
Paldiski	23.10.2006 – 31.10.2018	92.3%	92.3%	
Porvoo	1.1.2014 – 31.10.2018	87.0%	97.0%	
Hamina	1.1.1971 – 31.10.2018	100.0 %	100.0%	
Sillamäe	23.10.2006 – 12.5.2016	96.0%	96.0%	
Kronstadt	20.10.2005 – 31.10.2018	82.9%	81.4%	
Landsort	1.11.1886 – 14.9.2006	99.8 %	0%	not used in analysis
Hogland	29.4.2010 – 18.4.2018	22.8%	19.9%	3 h time interval, not used
St Petersburg	21.7.2004 – 31.10.2018	81.6%	79.5%	outside of model area, not used

Table 4.1: Tide gauge data of the northern Baltic Proper, the Gulf of Finland and the Bothnian Sea. For column "Usable data" a percentage of: good data (quality flag 1), probably good data (quality flag 2, data with no quality control performed (quality flag 0), and interpolated values (quality flag 8) are counted. For column "Good data" a percentage of data with quality flag 1 (good data) is counted. Swedish long time series had a big portion of the early data without quality control, marked with "no qc", these percentages were recorded in column "Notes". Tide gauge stations Landsort, Hogland, and St. Petersburg were not used in the analysis.

chosen and files with shorter time interval or of varying interval were processed. If there were data available on the hour, it was kept and other measurements done within the one hour period were ignored. In some situations, on the hour measurement was missing, while there were measurements done within the one-hour interval. We then linearly interpolated the missing value from the measurements that were within a one-hour time limit. In these situations, we also changed the quality flag to interpolated value.

There were some data gaps within the files, we added entries of missing value where the data were missing to get an estimate of how much of the data was really available from each station. In the table 4.1 we have calculated usable data percentages from all data entries within the time period measurements were available. For usable data we calculated data entries with quality flags of 1 - Good data, 2 - Probably good data, 0 - No quality control was performed, and 8 - Interpolated value. We also calculated the percentage of data with quality flag 1 - Good Data. The Swedish time series were long and they started to implement the current quality control system fairly recently. For example Stockholm tide gauge time series have quality control indicating good data from December 2007. For that reason, the percentages of good data are quite low. For data from Sweden, we also calculated the percentage of quality flag 0 - No quality control was performed and are presenting it in the notes section of the table.

Tide gauge data were plotted to see if there were irregularities that might affect the quality of the surface interpolation. Some spikes that were not seen in other tide gauges were examined and if thought suspicious, flagged not to be used in the analysis. In figure 4.1 there are examples of a problem in data from Hel in September – October 2006 where the sea level suddenly jumps suspiciously.



(a) Hel sea levels (in centimeters) September 2006.

(b) Hel sea levels (in centimeters) in October 2006.

Figure 4.1: Example of a problem found in the CMEMS tide gauge data. There is a sudden change in the tide gauge time series of Hel, Poland in (a) and (b).

Tide gauge data are in different original height systems. To convert the height systems from national reference heights into common height system EVRF 2007 a map provided by the German Federal Agency of Cartography and Geodesy (2017) in figure 4.2 was used.

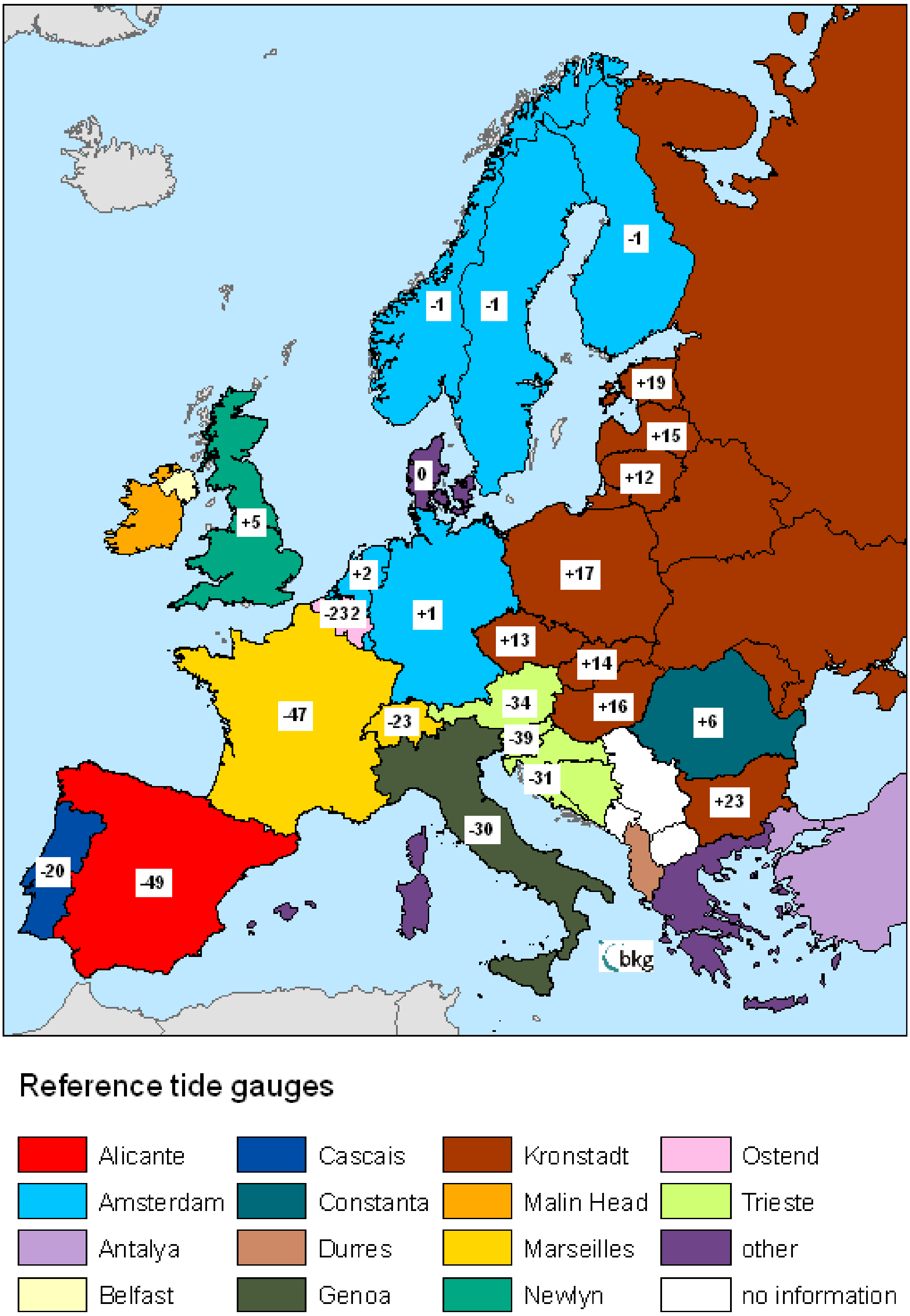


Figure 4.2: Change to EVRF 2007 from national reference heights in Europe according to German Federal Agency of Cartography and Geodesy (2017).

4.1.2 Interpolating the Sea Height Surfaces

A surface interpolation from tide gauge measurements was done with Python's function scipy.interpolate.Rbf from the SciPy's Interpolate package. It uses radial basis functions to interpolate values from n-dimensional scattered data based on their distance to data points. The functions were tested with a sample of tide gauge data. "Thin plate" function was chosen. (SciPy.org, 2019)

Data with quality flags of 1 - Good data, 2 - Probably good data, 0 - No quality control was performed, and 8 - Interpolated value, were used in the surface interpolation. Interpolation was made for the time period of 1.1.2007–31.12.2016. Interpolation was done with one hour time interval.

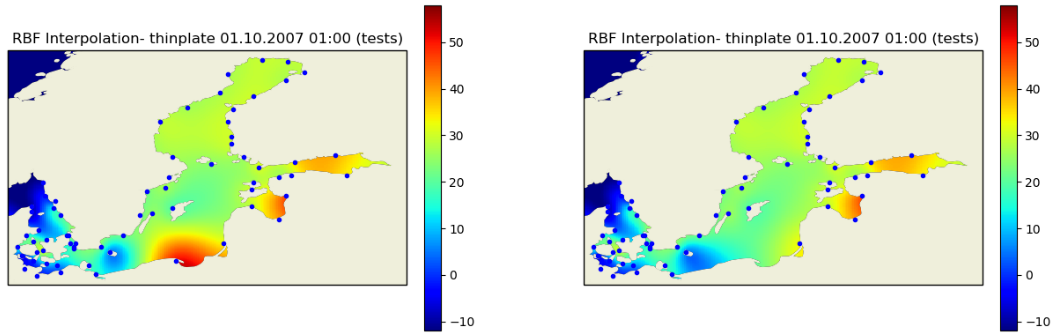
The grid covered latitudes 53.98°N – 65.86°N and longitudes 9.05 °E – 30.12 °E, with grid resolution of Δ latitude = 0.0333°and Δ longitude = 0.0535°. The grid matches the grid in files of NEMO-Nordic reanalysis product.

There were data availability issues with south-eastern Baltic Proper as described in section 3.1.5 and some problematic data shown in figures 4.1 was found. We made some tests on how sensitive the surface would be for missing data. In Figure 4.3 there are 2 interpolated sea level surfaces as maps. Blue dots represent the tide gauge station used in the interpolation. The first map 4.3a is the original version. Second map 4.3b has the tide gauge station Hel from Poland removed from the interpolation. Removing that station, made such a big difference to the interpolation surface, in a very large area of south-eastern Baltic Proper, that it would change completely the interpretation of the sea level situation. Since our research question was to determine if the surface interpolation from tide gauge methods could be a usable approximation of the sea surface height, we decided to limit the area of our analysis to the northern Baltic where there was a good availability of tide gauge data in a dense enough formation to warrant the use of interpolation estimates. Area for the analyses was cut from latitude 58.7.

4.1.3 Problems Found in the First Interpolated Surfaces and a New Surface Interpolation

After we made the sea level surface interpolation, we plotted it with the tide gauge time series and the NEMO-Nordic sea levels, in the location of the tide gauge station, to evaluate the fit. In some of the plots in the Gulf of Finland we saw undulation with an interval of three hours. The effect was largest in the Hogland tide gauge station. In figure 4.5 we have an example of this from Hogland and Hamina tide gauges in July 2016. The problem was that Hogland tide gauge time series was made with a three-hour interval instead of a one-hour interval. Therefore every third interpolated surface had Hogland data affecting the interpolation, while the others didn't. When sea level values from Hogland were not similar enough to the values in the surrounding tide gauge stations, this undulation appeared.

This effect demonstrated how big an impact one outlier tide gauge station had on the interpolated surface. Tide gauges from the area of Northern Baltic Proper, the Gulf of



(a) Original surface interpolation

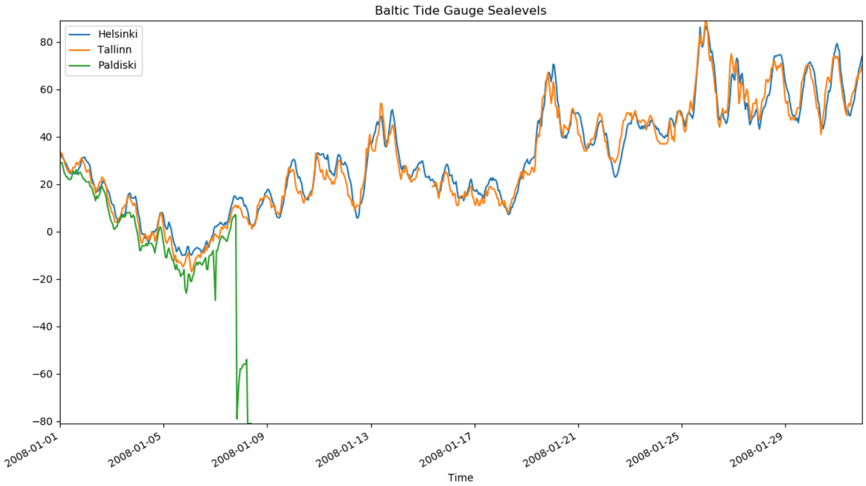
(b) Surface interpolation without data from Hel

Figure 4.3: Testing how much the sea level surface interpolation from tide gauge data would change if tide gauge data from Hel, Poland would be removed from the interpolation. Heights are in centimeters in EVRF2007.

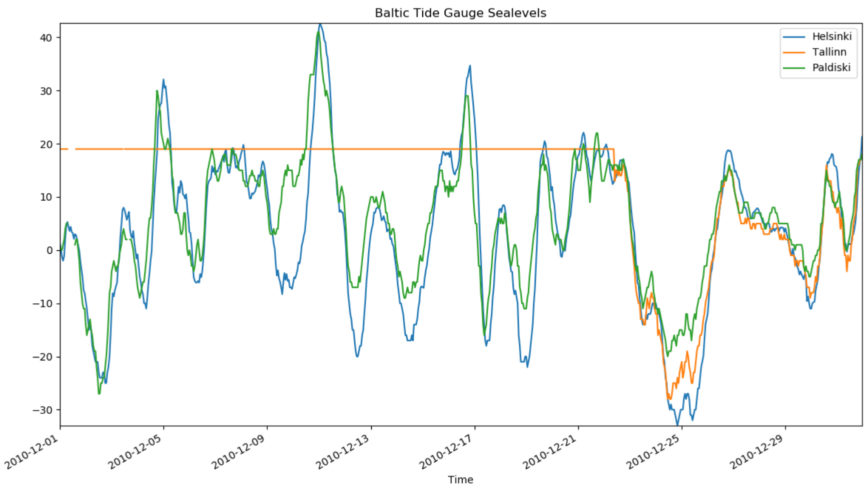
Finland and the Bothnian Sea were then grouped together by location and plotted into the same figure to see if there are more problematic measurements that could interfere with the sea surface interpolation. The plots were made from hourly measurements one month and one group at a time from January 2007 to December 2016. All figures were then inspected to see if there were patterns not seen with other tide gauges in the area. Special consideration was also placed on situation where the automatic test done by CMEMS had resulted in the removal of some data but had left some short periods of data between the removed time periods. Suspicious data was flagged not to be used in the analysis. In figures 4.4a and 4.4b there were few types of problems we saw in the data files.

A new surface interpolation was made with more carefully checked data and tide gauge measurements of Hogland station were removed completely. The area was cut from latitude 58.7 and only the tide gauge stations north of it were used for the new interpolation.

While making map representations of the new surfaces for chapter 5, color bar was set to represent values between -20 cm to 100 cm. This range was then compared to the original tide gauge data sets and from all tide gauge data in the northern Baltic (from tide gauge stations in figure 3.3) approximately 1.94% were outside of this range (1.0% above 100 cm and 0.94% values under -20 cm).

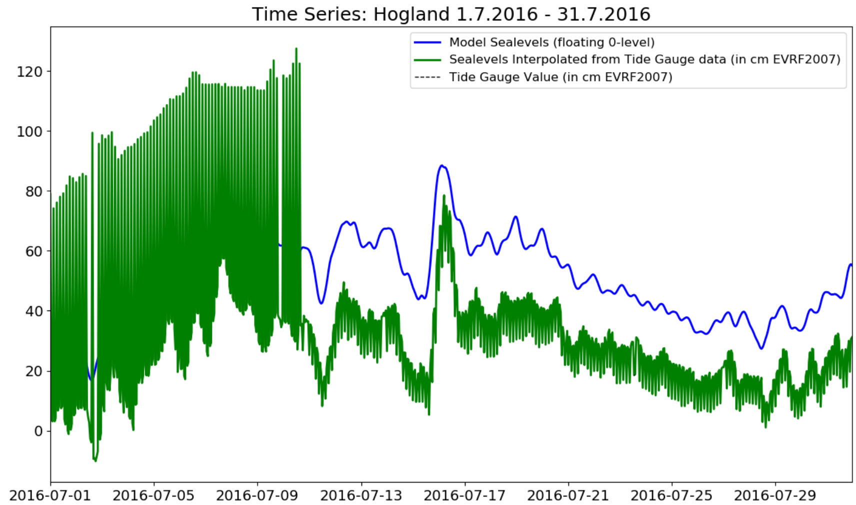


(a) Sea levels (in centimeters in EVRF2007) of Helsinki, Tallinn and Paldiski tide gauge station in January 2008.

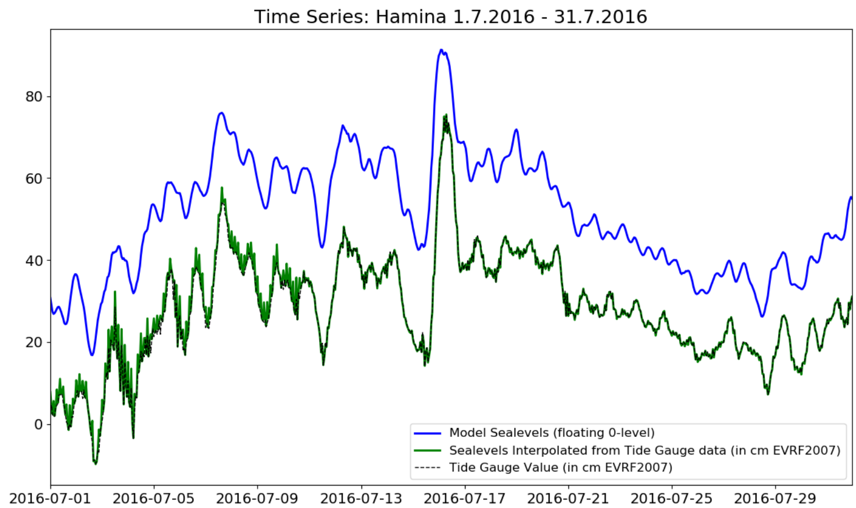


(b) Sea levels (in centimeters in EVRF2007) of Helsinki, Tallinn and Paldiski tide gauge station in December 2010.

Figure 4.4: Some problems in the CMEMS tide gauge data set.



(a) Interpolated Sea Levels (in green) and NEMO-Nordic reanalysis Sea Levels (in blue) in Hogland tide gauge station in July 2016. Heights are in centimeters in EVRF2007.



(b) Interpolated Sea Levels (in green) and NEMO-Nordic reanalysis Sea Levels (in blue) in Hamina tide gauge station in July 2016. Heights are in centimeters in EVRF2007.

Figure 4.5: There is a three-hour periodical wave seen in a figure 4.5a whenever Hogland station tide gauge values are different enough from the tide gauge values of nearby stations. In this figure, there are possibly erroneous values at the beginning of the month in the Hogland data file and the undulating effect is big enough to be seen also in the interpolated values of Hamina tide gauge station in figure 4.5b.

4.2 Comparing the Interpolated Sea Level Surfaces and the NEMO-Nordic Reanalysis Product Sea Levels

To be able to compare the sea level surfaces and the NEMO-Nordic reanalysis sea levels with the original tide gauge data we needed to find the model grid square that corresponded with the tide gauge station location. The tide gauge station of St. Petersburg was outside of the reanalysis model area and therefore it was decided to be left outside of the analysis.

The shoreline is often broken up with coves and peninsulas and the model grid squares are approximately 4.1 kilometers by 3.7 km, this means some tide gauges station locations on the shoreline were land squares in the model. In these situations, the closest sea grid square was chosen for the comparisons. This was done by checking the neighbouring grid squares if they were water and then calculating the distance from the tide gauge location to the midpoints of the grid squares that were defined as sea grid squares. The closest match was chosen. Furthest tide gauge station from the closest sea grid square was Pietarsaari, its distance to the nearest sea grid square middle point was 12.4 km.

In addition to the tide gauge location, we took three points from a central location in the Bay of Bothnia, the Bothnian Sea and the Gulf of Finland to compare the sea surface interpolation and the NEMO-Nordic reanalysis sea levels. The locations for the comparisons are presented in the figure 4.6.

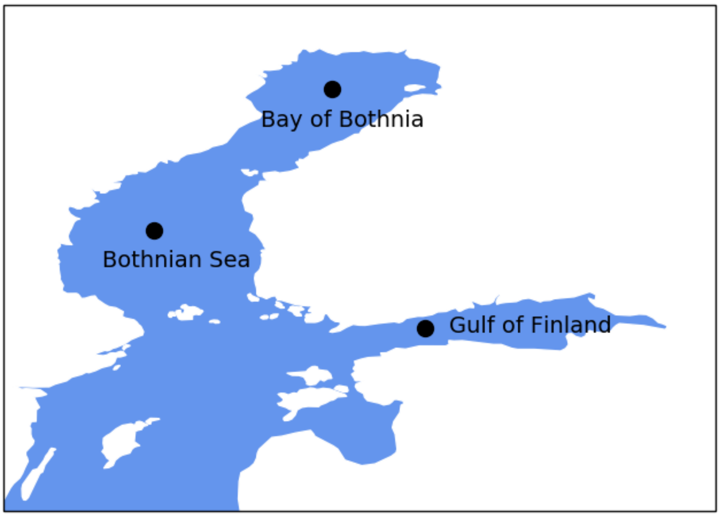


Figure 4.6: Locations where we compared the sea level surface interpolation and the modelled sea levels. The point in the Bay of Bothnia is in latitude 65.0 °N and longitude 23.0 °E, the point in Bothnian sea is in latitude 62.0 °N and longitude 19.2 °E and the point in the Gulf of Finland is in latitude 59.9 °N and longitude 25.0 °E.

5 Results

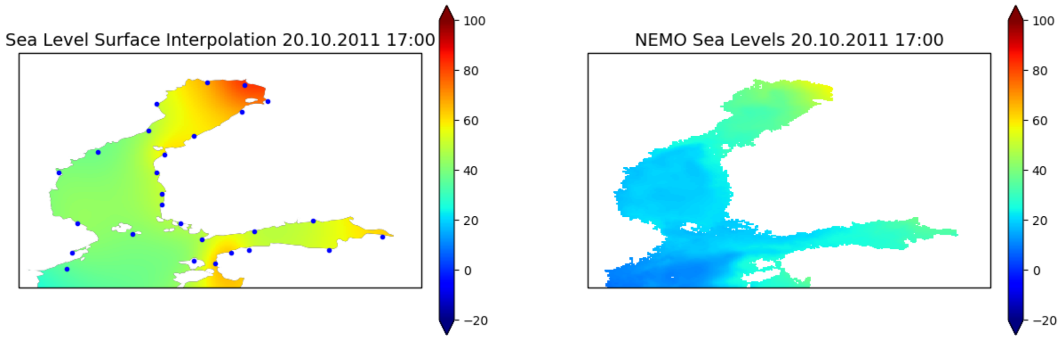
5.1 Hourly Maps of Interpolated Sea Level Surfaces and Modelled Sea Levels in the northern Baltic Sea

We made hourly maps of interpolated sea level surfaces as well as NEMO-Nordic reanalysis sea levels for the area of Bothnian Bay, the Bothnian Sea, northern Baltic Proper and the Gulf of Finland. In figure 5.1 there are two examples of these map pairs. The surfaces interpolated from tide gauge measurement are on the left and NEMO-Nordic reanalysis sea levels on the right. Figure 5.1a is from 20.10.2011 at 5pm and figure 5.1b is from 29.1.2016 at 7pm. The blue markers in the surface interpolation map are the locations of the tide gauges used for the interpolation.

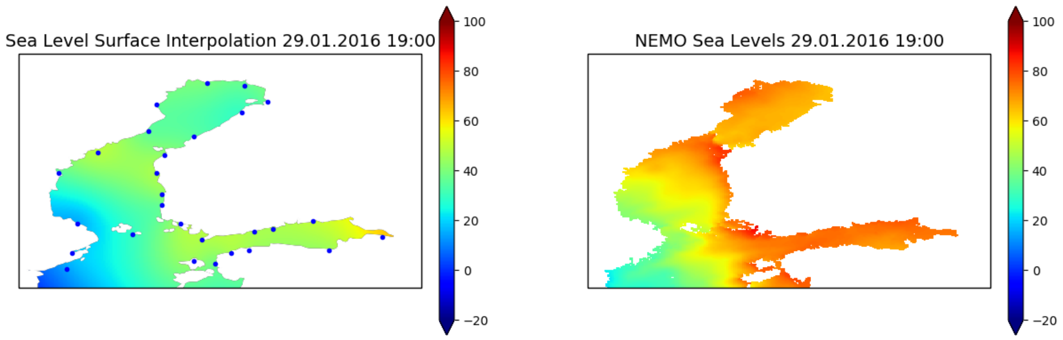
There is a noticeable difference with the sea levels with both of the picture pairs. Surface interpolation on the top row has higher overall values than the NEMO-Nordic comparison. Difference is roughly of the order of 20 cm. On the lower picture pair, the reversed is happening, with the modelled map having roughly 30 cm higher overall values than the surface interpolation.

In the surface interpolation of 2011 in figure 5.1a, there are high sea level values in the north-eastern part of the Bothnian Bay. The same is seen in the modelled map, though in different colors because of the difference in overall sea level. In the Bothnian Sea, the modelled map shows higher values near the north-eastern coast. This is not present in the surface interpolation map as strongly. Instead, the gradient is smoother towards the west. In the Gulf of Finland, the modelled map shows high values both in the eastern part of the gulf and also on the coast of Estonia compared to the sea levels on the coast of Finland to the north. On the surface interpolation, there is a gradient in the eastern part but also higher values in the west towards the Baltic Proper. Difference between the sea levels in the Estonian coast and Finnish coast is not seen in the surface interpolation.

In the image pair in figure 5.1b, the modelled sea levels show much higher values than the interpolated surface. In the surface interpolation and in the modelled image, there is a sea level gradient in the Bothnian Sea perpendicular with the shape of the basin. The gradient seems to be quite similar in both images. Though the Bothnian Bay is also presented similarly in both maps, the area of Kvarken (between the Bothnian Bay and the Bothnian Sea), however, has a very strong gradient in the modelled map that is much smoother in the surface interpolation. In the area from the south-western coast of Finland to the coast of Sweden in the northern Baltic Proper, there is a gradient in direction from the south-west to the north-east in both the surface interpolation and the modelled map, but there is more pattern in the modelled map that's missing in the surface interpolation.



(a) Sea level surface interpolation from tide gauge measurements on the left and NEMO-Nordic reanalysis product sea levels on the right for 20.10.2011 at 5 pm. Both heights are in centimeters and the interpolated surface is in height system EVRF2007.



(b) Sea level surface interpolation from tide gauge measurements on the left and NEMO-Nordic reanalysis product sea levels on the right for 29.1.2016 at 7 pm. Both heights are in centimeters and the interpolated surface is in height system EVRF2007

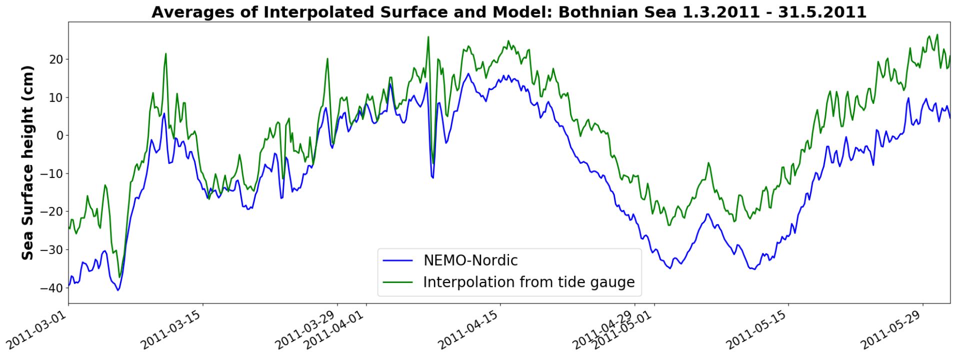
Figure 5.1: Sea level surface interpolation from tide gauge measurements and NEMO-Nordic reanalysis product sea levels on two different occasions. The blue markers on the left maps are tide gauge stations used for the interpolation. The area in the maps covers Bothnian Bay, Bothnian Sea, northern parts of Baltic Proper, and the Gulf of Finland. The color bar presents the sea levels in centimeters.

5.2 Time Series of Interpolated Sea Level Surfaces and Modelled Sea Level Heights

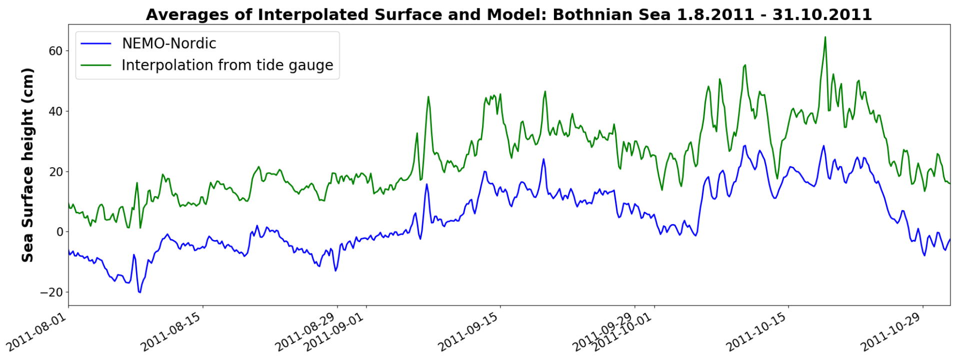
Time series of sea level surfaces interpolated from tide gauge measurements and NEMO-Nordic reanalysis sea levels were made for three locations presented in figure 4.6. In figure 5.2a there is time series of interpolated sea level surface and the modelled sea level, with four-hour resolution, for a point in the Bothnian Sea from 1.3.2011 to 31.5.2001. The lower figure 5.2b is for a time period of 1.8.2011 – 31.10.2011. The interpolated surface has similar features in variability as the modelled sea level, though the interpolated time series has more variability on the small time scales than the modelled sea levels. In the upper, springtime figure 5.2a, at the beginning of March, there is approximately 20 centimeter difference with the sea surface height between the two data. After few days the difference becomes smaller (varies between 0–10 cm) and stays that way until mid-April, where the difference between the two data sets starts to grow to about 15 centimeters. Similar patterns were seen in figures from other years as well, though the timing of when the data sets started to diverge in the spring varies somewhat. The amplitude of peaks and dips in the time series are smaller in the modelled data than in the interpolated data. In the lower, autumn figure 5.2b, the difference between the data sets is 15–20 centimeters. The sea levels seem to vary similarly for both time-series.

In the figures 5.3a and 5.3b there are similar time series for a point in Bothnian Bay for the same time period. The overall sea levels with the interpolated and the modelled time series seem to be better correlated in Bothnian Bay than in the Bothnian Sea. Phenomena of the difference between the two time series being smaller, 0–10 centimeters, during the spring continues throughout the time period (to the end of May) in the Bothnian Bay. In the autumn figure the difference between the data sets is approximately 15-20 cm. There are peaks especially in October where the amplitude of the peak in the surface data is much bigger than in the modelled data, in those situations the difference between the data sets can grow to approximately 35–40 cm.

In figures 5.4a and 5.4b there are time series for interpolated and modelled sea levels for a point in the Gulf of Finland. The difference between the time series in the springtime image is better (5–10cm) until the beginning of April, then the difference between the two data sets grows to approximately 15–20cm. In the autumn image, the difference between the two data sets is about 20–25 centimeters for the presented time period. There is more small amplitude variation with the interpolated time series than with the modelled one. This is especially visible at the end of April in figure 5.4a.

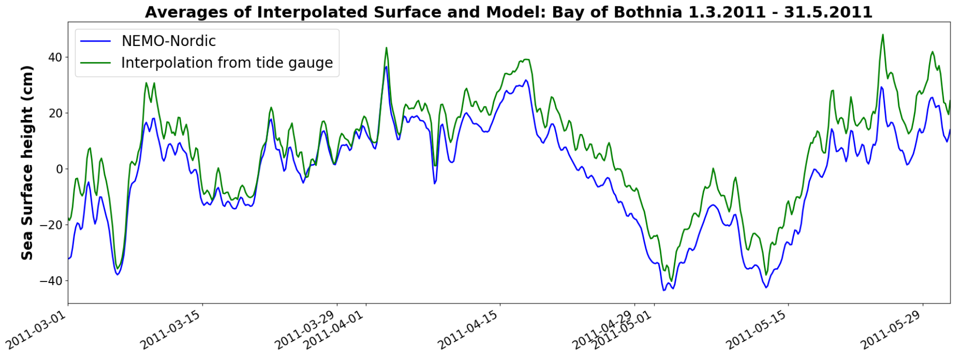


(a)

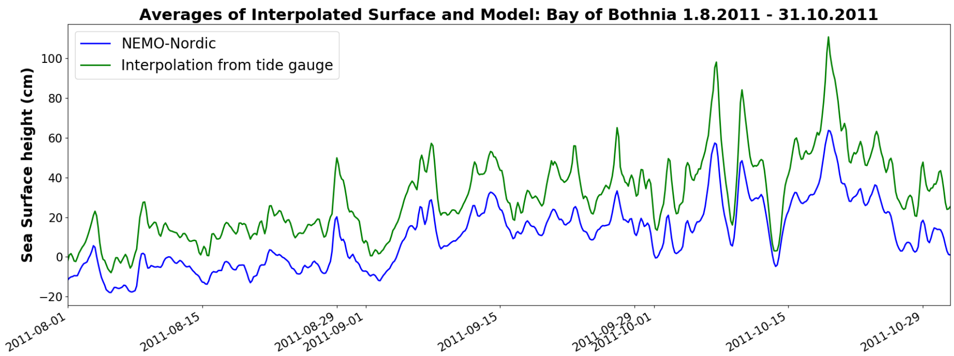


(b)

Figure 5.2: Four hour averages of sea levels interpolated from tide gauge measurements and NEMO-Nordic modelled sea levels for location in Bothnian Sea (lat 62.0°N, lon 19.2°E). The upper figure 5.2a is for the time period of 1.3.2011– 31.5.2011 and the the lower figure 5.2b is for the time period 1.8.2011–31.10.2011. Sea levels are in centimeters and the interpolated surface is in the height system EVRF2007.

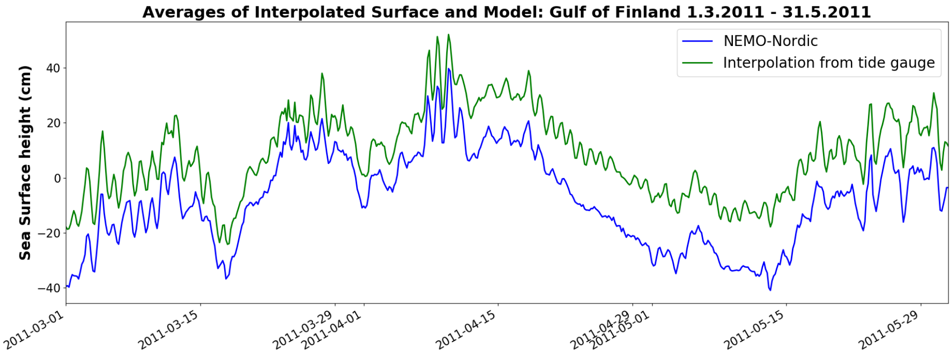


(a)

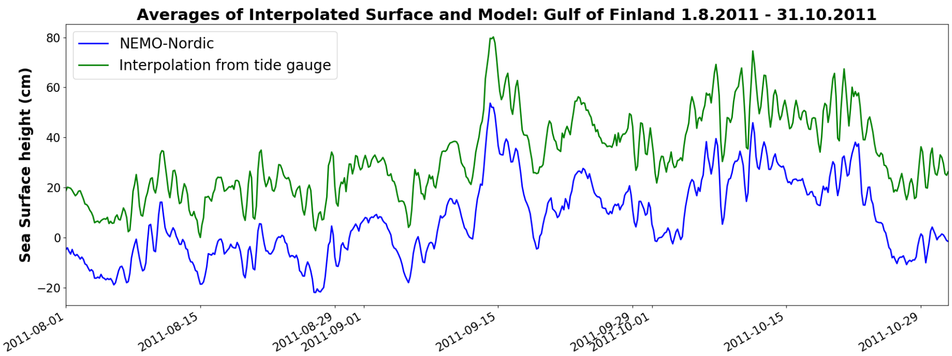


(b)

Figure 5.3: Four hour averages of sea levels interpolated from tide gauge measurements and NEMO-Nordic modelled sea levels for location in Bothnian Bay (lat 65.0°N, lon 23.0°E). The upper figure 5.3a is for the time period of 1.3.2011– 31.5.2011 and the lower figure 5.3b is for the time period 1.8.2011–31.10.2011. Sea levels are in centimeters and the interpolated surface is in the height system EVRF2007.



(a)



(b)

Figure 5.4: Four hour averages of sea levels interpolated from tide gauge measurements and NEMO-Nordic modelled sea levels for location in Gulf of Finland (lat 59.9°N, lon 25.0°E). The upper figure 5.4a is for the time period of 1.3.2011– 31.5.2011 and the the lower figure 5.4b is for the time period 1.8.2011–31.10.2011. Sea levels are in centimeters and the interpolated surface is in the height system EVRF2007.

5.3 Correlation between the Interpolated Sea Level Surfaces and the Modelled Sea Level Heights

The correlation and the median sea level is examined in two parts. First, we have the ten-year period of 1.1.2007-31.12.2016 where correlation is computed between interpolated sea levels and NEMO-Nordic reanalysis product sea levels from hourly data for the tide gauge station locations and for the three comparison points in the Bay of Bothnia, the Bothnian Sea and the Gulf of Finland. We also look at the medians of the two data sets in these locations for the ten-year period. In the latter section, we take a look on the correlations computed for each year from hourly data for the three comparison points. We also examine the yearly median levels of both of the data for years 2007-2016.

5.3.1 Correlation with the Ten-Year Period of Data for the Tide Gauge Stations and Comparison Point Locations

Median of interpolated sea levels, median of NEMO-Nordic reanalysis product sea levels and a correlation between the interpolated sea levels and NEMO-Nordic sea levels computed from hourly data for the time period 1.1.2007-31.12.2016 is shown in table 5.1. The three first stations are selected to present mid-basin points in the Bothnian Sea, the Bay of Bothnia and the Gulf of Finland. The three points are shown in the map 4.6. The remaining stations are tide gauges in the Bay of Bothnia, the Bothnian Sea, the Gulf of Finland and the northern Baltic Proper shown in figure 3.3. The correlation varied between stations from 0.59 in Sillanmäe to 0.77 in Kronstadt. The median of the correlations was 0.69.

With the stations in the Bay of Bothnia, the correlation is better with the northernmost stations; Kemi having a correlation of 0.75 and more southern stations in Ratan and Pietarsaari having lower correlations of 0.69 and 0.70. The middle of the bay point has a correlation of 0.71. In the Bothnian Sea tide gauge stations the correlation is between 0.64–0.68 and the comparison point in the middle of the basin has a correlation of 0.63. In the Gulf of Finland, the furthest stations in the east have a higher correlation with Krondstadt having 0.77 and Hamina 0.75. Helsinki, Porvoo, and Tallinn have a correlations between 0.70–0.73. Sillanmäe tide gauge station seems to be an exception from this pattern, being further in the east but only having a correlation of 0.59, the lowest in the data set. Western parts of the Gulf of Finland and the northern Baltic Proper have correlations ranging from 0.62 to 0.72 the higher values are in Turku, Rohukula and Heltermaa. The point in the middle of the Gulf of Finland has a correlation of 0.71, similar to the close by tide gauge stations.

The difference between the medians of the interpolated surface and the model reanalysis are quite big, the mean of the difference is 8.7cm. The medians of interpolated surfaces are higher than the medians of the modelled sea level values for all the stations. The median values of the interpolated and the modelled sea levels are most similar in the stations of Bay of Bothnia and have the biggest differences in the Gulf of Finland stations. The difference in the median values of both of the data for the point in the Bay of Bothnia is 3.9cm, north of it in Kemi tide gauge station the difference is 2.9cm and south of it in Ratan tide gauge station the difference is 1.7cm. For the point in the Bothnian Sea, the difference in medians of the two data sets is 6.3cm, north of it in the Skagssudde tide gauge station the difference is 1.6cm and south-east of it in Rauma the difference is 10.2cm. Generally, in the Bothnian Sea area, the difference is higher in the eastern tide gauge stations than in the western tide gauge stations. For the point in the Gulf of Finland, the difference is 13.7cm. For the nearby tide gauge station in Helsinki, the difference is 12.6cm. For the northern Baltic Proper and the Gulf of Finland the difference between the medians of the two data set is smallest in the west and north; 9.3cm in Degerby and 11.4cm in Stockholm. The difference in the medians grows towards the east, in Kronstadt the difference between the two medians is 22.3cm.

5.3.2 Yearly Correlation Calculated for a Points in the Bay of Bothnia, the Bothnian Sea and the Gulf of Finland

A correlation for each year for the time period of 2007-2016 and for the location in three mid-basin points in the Bay of Bothnia, the Bothnian Sea and the Gulf of Finland are presented in the table 5.2. The correlation for the Bay of Bothnia point varied between 0.93 and 0.97, the year 2014 had the worst correlation and year 2007, 2008 2011, and 2013 had a correlation of 0.97. Median value for correlation for the point in the Bay of Bothnia was 0.96. The correlation for the point in the Bothnian Sea was lowest also in 2014 (0.91) and the best correlation (0.98) was in the year 2008. The median for the correlation of Bothnian Sea was 0.95. The correlation for the point in the Gulf of Finland was worst in the year 2012 (0.93), the best correlation in the period (0.98) was in 2008. The median value for the correlation of the Gulf of Finland was 0.96. Best years for correlation for the three points were in 2008, 2007 and 2013. The worst correlations for the three points were in 2014 and 2012. All correlations counted for each year were significantly better than the overall correlation for these points presented in table 5.1.

In the table 5.2 there are medians of sea level heights of the interpolated surface from tide gauge measurements and medians of the NEMO-Nordic reanalysis product sea level heights for each year in the period of 2007-2016.

Median of sea level heights from the interpolated surfaces in the Bay of Bothnian comparison point ranges from 0.40 cm (in the year 2014) to 27.16 (in the year 2007). Median of the sea surface interpolation for the Bothnian Sea is between -2.68 cm (in the year 2014) and 21.38 cm (in the year 2007). For the point in the Gulf of Finland, the lowest median value was 5.76 (in the year 2014) and the highest 29.47 cm (in the year 2007). The difference in medians between the years of 2007 and 2014 is 26.8 cm for the point in the Bay of Bothnia, 24.1 cm for the point in the Bothnian Sea, and 23.7 for the point in the Gulf of Finland. For the interpolated sea levels the median was highest in the Gulf of Finland for all of the years and the lowest in the Bothnian Sea. The difference between medians of the points in the Gulf of Finland and the Bothnian Sea were the smallest 7.34 cm in the year 2011 and

Station	**Median of Interp. Surface**	**Median of Model**	**Corre-lation**
Bay of Bothnia	12.28	8.37	0.71
Bothnian Sea	8.94	2.62	0.63
Gulf of Finland	17.95	4.25	0.71
Kemi	13.08	10.20	0.75
Kalix-Storön	13.01	10.11	0.74
Oulu	12.62	9.83	0.74
Furuögrund	9.74	9.31	0.71
Raahe	11.73	8.70	0.73
Ratan	9.67	7.97	0.69
Pietarsaari	11.55	7.62	0.70
Skagsudde	7.10	5.50	0.65
Vaasa	11.34	5.65	0.68
Spikarna	7.71	4.72	0.64
Kaskinen	13.20	4.48	0.67
Pori	13.57	4.16	0.67
Rauma	13.49	3.31	0.67
Forsmark	9.80	3.87	0.64
Turku	14.07	4.08	0.69
Degerby	11.20	1.91	0.65
Stockholm	12.70	1.30	0.62
Landsort	11.36	-0.49	0.62
Hanko	16.17	3.21	0.69
Lehtma	13.47	2.01	0.66
Heltermaa	14.61	2.85	0.71
Rohukula	15.07	3.09	0.72
Helsinki	17.56	4.97	0.73
Tallinn	17.32	3.54	0.70
Paldiski	14.34	3.07	0.67
Porvoo	18.14	5.67	0.73
Hamina	19.49	7.29	0.75
Sillamäe	23.34	6.11	0.59
Kronstadt	31.01	8.74	0.77

Table 5.1: Median of interpolated sea levels (in cm in EVRF2007), median of NEMO-Nordic reanalysis product sea levels (in cm) and correlation between the interpolated sea levels and NEMO-Nordic sea levels counted from hourly data with time period of 1.1.2007-31.12.2016 for three selected comparison points in middle of the basins of Bay of Bothnia, Bothnian Sea and Gulf of Finland as well as northern Baltic tide gauges.

the biggest 10.78 cm in the year 2015.

For the median of the modelled sea level values from the NEMO-Nordic reanalysis product the lowest medians were for the point in the Bay of Bothnia (in 2010) -13.29, (in 2010) for the point in the Bothnian Sea -15.73 and for the point in the Gulf of Finland -12.97 cm (in the year 2013). The highest medians for all of the three points in the year 2015 were: 51.43 for the Bay of Bothnia, 47.64 for the Bothnian Sea and 48.28 for the Gulf of Finland. The difference in the highest and lowest median for each of the years was 64.7 cm for the Bay of Bothnia, 64.4 cm for the Bothnian Sea and 61.3 cm for the Gulf of Finland. Median was highest for most of the years in the point in the Bay of Bothnia with the exception of the year 2010 where the highest median was in the Bothnian Sea. The lowest median was generally in the Gulf of Finland but in the years 2014 and 2016 the lowest median were in the Gulf of Finland. The biggest differences between the median of the points were in 2007 6.6 cm and lowest in 2010 2.8 cm.

The median is mostly larger for the interpolated values than for the modelled values, but in years 2014, 2015 and 2016 the medians of the modelled sea levels are higher than the interpolated median. There is a large difference of the median values for the two time series in each year, the difference between the medians of the two data sets varies between the stations and the years but is between 13 cm to 34 cm. Taking a mean of the difference of the median values for all three points from 2007 to the end of 2013 is 19.3 cm with interpolated sea levels being higher. From 2014 to the end of 2016 the modelled sea levels are higher and the mean difference between the median values is 27.7 cm.

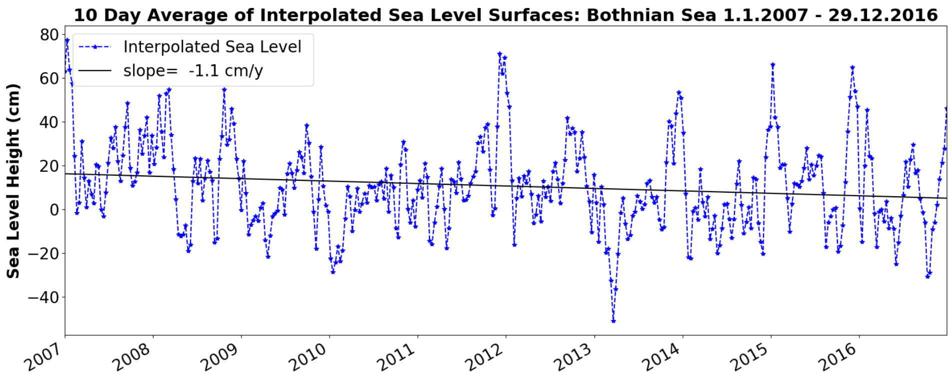
Year	Station	Median of Interp. Surface	Median of Model	Correlation
2007	Bay of Bothnia	27.16	6.87	0.97
	Bothnian Sea	21.38	0.30	0.97
	Gulf of Finland	29.47	2.44	0.97
2008	Bay of Bothnia	22.02	5.03	0.97
	Bothnian Sea	19.79	1.69	0.98
	Gulf of Finland	27.64	2.34	0.98
2009	Bay of Bothnia	8.09	-10.55	0.96
	Bothnian Sea	4.36	-13.46	0.95
	Gulf of Finland	13.61	-12.91	0.96
2010	Bay of Bothnia	2.86	-13.29	0.96
	Bothnian Sea	3.08	-15.73	0.96
	Gulf of Finland	11.88	-12.92	0.97
2011	Bay of Bothnia	16.60	3.00	0.97
	Bothnian Sea	13.00	-3.13	0.96
	Gulf of Finland	20.38	-1.80	0.97
2012	Bay of Bothnia	17.05	3.78	0.94
	Bothnian Sea	13.53	-0.77	0.93
	Gulf of Finland	23.18	-0.45	0.93
2013	Bay of Bothnia	4.68	-8.68	0.97
	Bothnian Sea	1.02	-13.27	0.97
	Gulf of Finland	10.15	-12.97	0.96
2014	Bay of Bothnia	0.40	30.00	0.93
	Bothnian Sea	-2.68	26.68	0.91
	Gulf of Finland	5.76	25.70	0.94
2015	Bay of Bothnia	20.89	51.43	0.95
	Bothnian Sea	16.09	47.64	0.94
	Gulf of Finland	26.87	48.28	0.96
2016	Bay of Bothnia	6.10	40.03	0.96
	Bothnian Sea	2.70	35.40	0.94
	Gulf of Finland	13.38	34.07	0.95

Table 5.2: Median of interpolated sea levels (in cm in EVRF2007), a median of NEMO-Nordic reanalysis product sea levels (in cm) and a correlation between the interpolated sea levels and NEMO-Nordic sea levels counted for three selected comparison points in the middle of the basins of the Bay of Bothnia, the Bothnian Sea and the Gulf of Finland. The values were calculated from hourly data with the time period of one year for each year between 2007 and 2016.

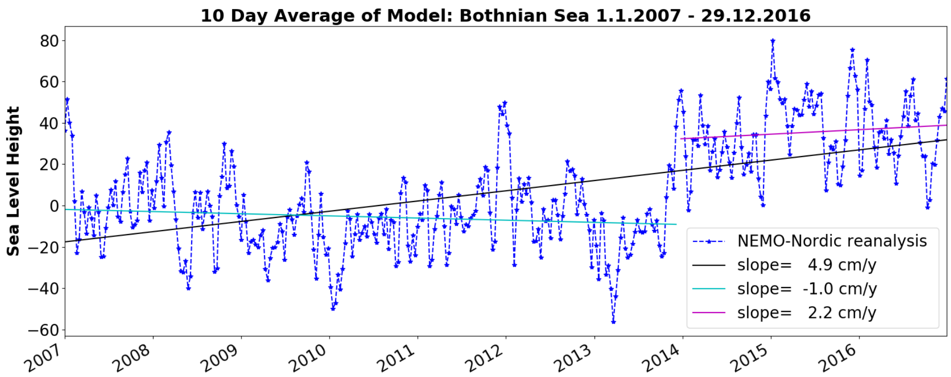
5.4 Trends in The Data Sets for the Period of 2007–2016

In a figure 5.5a there is a ten-day average of interpolated sea level surface from the mid-basin point in the Bothnian Sea for the time period of 2007–2016. A linear fit was calculated and it gave a slope of -1.1 centimeters per year. In a figure 5.5b there is a ten-day average of the NEMO-Nordic reanalysis sea levels from 2007–2016. The linear fit for the whole time period is 4.9 centimeter per year. However, there seems to be a jump in the sea levels between 2013 and 2014. For this reason, also fit in pieces is checked, for the first part up till the end of 2013 the fit would be with a slope of -1.0 cm per year and after the beginning of 2014, the fit would be 2.2 cm per year. For the time period 2007-2013 there is only small difference in the slope of the linear fit of the two data set, however there is a mean sea level difference of nearly 20 centimeters. In appendices 6.2 there are similar figures for the points in the Bothnian Bay and the Gulf of Finland.

In figure 5.6 there is a 60-day rolling average for the point in the Bothnian Sea of the difference between the sea levels interpolated from the tide gauge measurements and the NEMO-Nordic reanalysis. From 2007 until the end of 2013 the interpolated sea levels have been higher than the modelled sea levels. There is also a yearly pattern noticeable where there is a minimum for the difference between the data sets in early spring until end of year 2013. In the winter 2013-2014, there is a sudden drop between the difference and from there on the model sea levels are higher than the interpolated sea levels. In appendices 6.2 there are similar figures for the points in the Bothnian Bay and the Gulf of Finland.



(a) Ten-day average of interpolated sea levels from tide gauge measurements in EVRF 2007 heights in centimeters. The black line is a linear fit with the slope of -1.1 cm per year.



(b) Ten-day average of NEMO-Nordic reanalysis sea levels in centimeters. The black line is a linear fit with a slope of 4.9 cm per year.

Figure 5.5: Ten-day averages of interpolated sea levels from tide gauge measurements and NEMO-Nordic reanalysis sea levels for a point in Bothnian Sea (lat 62.0°N, lon 19.2°E) for the period of 2007-2016.

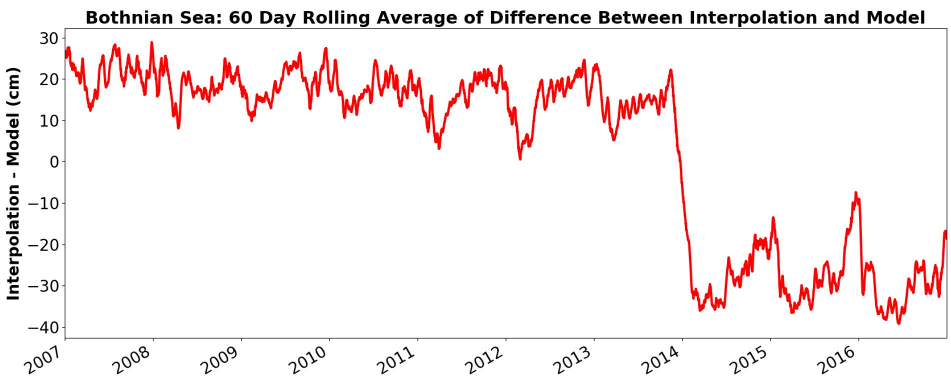


Figure 5.6: 60-day rolling average of difference between interpolated sea levels from tide gauge measurements and NEMO-Nordic reanalysis sea levels for a period of 2007-2016.

6
Discussion and Conclusions

In this chapter, we first go through and discuss the key results from the chapter 5. Then we take a critical look at the used data set and the methods. With the next section, we discuss our answer to the research question and analyse further the usability of the interpolated surface and the results we got. We then ponder about possible future research topics. Finally, we conclude the thesis with a summary of what was done and what our main results were.

6.1 Discussion

6.1.1 Key Results

Key Results from Hourly Maps of Interpolated Sea Level Surfaces and Modelled Sea Levels in the northern Baltic Sea

The maps 5.1 presented in the section 5.1 showed surfaces interpolated from the hourly tide gauge measurements and hourly NEMO-Nordic reanalysis product sea levels. The areal mean values of both of the data sets were quite different, which can be seen from the overall color differences between the two maps. In the presented figures the difference between the sea levels between the data sets is in the order of 20–30 cm. With the 2011 map pair, the interpolated map had higher values and with the 2016 maps, the modelled map had higher values. Although there was a big difference in the mean, the variations from the mean were presented similarly in both maps.

Situations, where the gradient of the sea level was perpendicular to the shape of the basin, showed most similar in both interpolated and modelled maps. However, there is smoothing over sharp gradients in the interpolated surface and while the interpolation does present gradients between stations along the coastline quite well, it falls short describing gradients parallel to the shape of the basin i.e. from coast to coast. The interpolation creates a smooth gradual change where the model sea levels can have a strong gradient for example near the coastline. As the piling up of sea water can occur in the coastal areas (Leppäranta & Myberg, 2009; Lisitzin, 1974), the model's interpretation is more physical and thus probably more realistic.

Key Results from the Time Series of Interpolated Sea Level Surfaces and Modelled Sea Level Heights

The time series figures 5.2, 5.3 and 5.4 presented in the section 5.2 had three-month time ranges from March to May in 2011 and from August to October in 2011. The time series presented four-hour averages of the interpolated surfaces and the NEMO-Nordic reanalysis sea levels from the three mid-bay locations in the Bothnian Sea, the Bay of Bothnia and the Gulf of Finland.

A difference in the mean sea levels between the two data sets can be seen in most of the time series. For all three points of study, the difference between the surface and the model is smallest in the early spring varying between 0–10cm. With the Bay of Bothnia, the difference stays small for longer, while in the Gulf of Finland, the difference starts to grow at the beginning of April. For the point in the Bothnian Sea, the difference between the data sets starts to grow in mid-April. Outside of this spring minimum, the difference mostly varied between 15–25 cm.

There is also more variability in small time-scales with the interpolated data than with the modelled data, this is especially seen with the time series from the Gulf of Finland. There are also differences in the peaks and dips in the time series, that seem to have a higher amplitude with the interpolated surface than with the modelled sea levels. This can temporarily grow the difference between the two data sets to 35–40 centimeters.

Key Results from Correlation between the Interpolated Sea Level Surfaces and the Modelled Sea Level Heights

In section 5.3 correlations between the interpolated sea level surfaces and the NEMO-Nordic reanalysis products as well as the medians for both of the data sets were discussed. In the table 5.1 the values were calculated for the entire period of 2007–2016 for the tide gauge stations and the three comparison points. In the Table 5.2 the values were calculated for each year separately and for the three comparison points in the Bothnian Sea, the Bay of Bothnia and the Gulf of Finland.

For the ten-year period, the correlations between the data sets varied between 0.59–0.77, 0.69 being the median. With the Bay of Bothnia and the Bothnian Sea the correlation was best in the north and for the Gulf of Finland, the correlation was best in the east. So the further from the Baltic Proper, the better the correlation was in general. A tide gauge station of Sillanmäe was an outlier from this pattern having the worst correlation of the stations. The correlations for the comparison points in the middle of the basins were comparable with the correlation of the tide gauges in the area. The correlation for the point in the Bay of Bothnia was 0.71, the correlation for the point in the Bothnian Sea was 0.63 and the correlation for the point in the Gulf of Finland was 0.71.

The difference between the medians of the two data sets for the ten-year period was noticeable, medians of the interpolated surfaces were bigger than the medians of the modelled sea levels for all stations. The northern and western stations had the smallest difference between the medians of the two data sets and southern and eastern stations had the biggest difference. The middle basin points had comparable median values to those of the nearby tide gauge stations.

The correlations counted separately to each year between 2007–2016 for the three comparison points were much higher than the correlations counted for the 10-year period. The median correlation for the years 2007–2016 were 0.96 for the point in the Bay of Bothnia and the Gulf of Finland and 0.95 for the point in the Bothnian Sea.

The median values counted separately to each year of the interpolated surfaces have quite a big variation between years for example for a point in the Bay of Bothnia the median between the highest in the year 2007 and the lowest in the year 2014 is 26.8cm. However, for the modelled medians for the point in the Bay of Bothnia, the difference between the lowest year in 2010 and the highest year in 2015 is 64.7cm. The medians of the interpolated surfaces are generally larger than with the modelled sea levels. From 2007 to the end of 2013 the mean difference between the median for all points was 19.3 cm. In years 2014, 2015 and 2016 modelled sea levels were higher than interpolated sea levels with a mean difference of the medians for all points being 27.7 cm.

Key Results from Trends in The Data Sets for the Period of 2007–2016

In the section 5.4 in the figures 5.5 there were a time series of ten-day averages of both the surface interpolated from tide gauge measurements and the NEMO-Nordic reanalysis sea levels for the point in the Bothnian Sea. The time series was for the period of 2007–2016. A linear fit was calculated for the interpolated time series and it had a slope of -1.1 cm per year. According to Ekman (1996) apparent land rise value for the area is 7 mm per year for period of 1892-1991. For the modelled time series, a linear fit for the whole period was 4.9 cm per year. However, there was a noticeable jump in the levels in the middle of winter 2013–2014. A linear fit in pieces was also calculated, from 2007 until the end of 2013 there was -1.0 cm per year slope. From the beginning of 2014 to 2016 a slope of 2.2 cm per year was calculated. There is approximately 20 cm difference in the mean sea level between the interpolated and the modelled data for the years 2007-2013.

In figure 5.6 there was a 60-day rolling average of the difference between the two data sets. The change in the modelled sea levels in winter 2013–2014 changed the pattern considerably. Until then, there were some yearly patterns for the difference, with a minimum in the early spring.

Comparing the Key Results Together

There is a difference with the mean sea levels between the surface interpolated from tide gauge measurements and the NEMO-Nordic reanalysis product. From 2007 to the end of 2013 the mean difference is around 20 cm, with interpolated values being higher than modelled values. In figure 5.5 the difference can be seen in the level of the trend line for the interpolated surfaces and in the level of the trend line calculated in pieces for the modelled sea levels. Similar values can also be seen in the table 5.2 with the median values for of the data sets having a mean difference of 19.3 cm between the years 2007 and 2013.

From figure 5.6 we can see that there is quite a lot of variation within the difference. One of the causes for this variation is probably the difference in the amplitudes of the sea level spikes between the data sets as seen from the three-month time series figure 5.3. The difference in the sea levels in spikes can be of the order of 35–40cm. So even though the difference between the mean sea levels would be fairly constant, these spikes add to the difference in the rolling average values. This can partly also explain the minimum difference in the spring, because the variations of the sea levels are smaller. However, we also see that the data sets have a smaller difference between them during the spring in the figures of the three-month time series 5.2, 5.3 and 5.4.

The interpolation is made in a way that the difference between the interpolations and the tide gauge measurements i.e. the residual is small at the tide gauge locations. This means that the differences seen between the interpolated surface and the modelled sea levels has probably something to do with how the model calculates the sea level. An easy explanation would be that the model has a zero in different height than the tide gauge data, but this would not explain the spring situation with the sea level differences between the data sets being much closer to each other. Other possible reasons include the model having two open borders, the freshwater input or the fact that the model doesn't conserve the mass of the water, only volume.

Although the difference in sea levels of the two data sets in the tide gauge locations might be due to model's features, the mid-bay locations might still have some additional differences. The difference in the medians of the two data sets in the table 5.1 are comparable with the three points in the middle of the bay and the tide gauge locations. However, we didn't make comparisons like in the table 5.2 for each year for the tide gauge stations, and the medians of the model sea levels for the whole period are affected by the jump in the levels in mid-winter 2013–2014. Therefore we can't say conclusively, that there aren't additional effects on the mid-point locations.

There is a change in the mean sea levels of the NEMO-Nordic reanalysis in the mid-winter 2013–2014, seen in figure 5.5. After the jump, the model sea levels have a different linear fit than before, slope changing from -1.0 to 2.2. The same can be seen from the rolling average figure 5.6. This seems to be a problem with the model. There has been some discussion with Lars Axell, who wrote the Model Reanalysis Quality Information document, that this could have something to do with the open boundary forcing and that they will look into it. It is also worth mentioning, that the atmospheric forcing from Hirlam model changing resolutions between 2013–2014 (mentioned in the section 3.2), coincides with the jump. This jump and difference in the trend in 2014-2016 is probably the reason, why the correlation for the whole period, is much worse than when correlation calculated for each year separately.

6.1.2 Evaluation of Used Data Sets and Methods

Data Sets

We used tide gauge data from CMEMS and SMHI's open data services. Both data sets were quality controlled using automated procedures and on suspicious data inspection by an expert. Both data sets were quality controlled and given quality labels. We used data that was labelled to be good, probably good, interpolated value and uncontrolled data. Most of the data we used fell into the category of good data. However, a big portion of the available data from Sweden hadn't been through the quality control. This was due to the fact that the available time period was long and they had started to use the current quality control procedure fairly late for their archived data. For this reason, there may be some station on the coast of Sweden from where the data was not quality controlled at the beginning of our ten-year study period of 2007-2016.

The Quality Information Document of the CMEMS data (Wehde et al., 2017) evaluates the tide gauge accuracy number to be 1 centimeter. While examining the tide gauge data by plotting it as time series, problems were found, that effected the interpolated surface. There were, for example, big spikes that looked suspicious and could not be seen in plots of the nearby stations and occasions when the tide gauge record was the same value for a long period of time. The problematic data were removed. For the final version of the surface interpolation, all tide gauge data were checked by plotting it with the nearby stations.

The NEMO-Nordic reanalysis model was discussed in section 3.2. In the Quality Information Document of the model reanalysis product (Axell et al., 2018) the model sea levels were compared with the tide gauge data from Sweden and Denmark for the years in 1995, 2005 and 2015. The model's mean correlation with the tide gauge data was 0.95 and the mean RMS error 7 cm for the Baltic Sea. The document didn't explain how the differences in the sea levels were solved prior to calculating the RMS error. A likely explanation is that the yearly mean of both tide gauge data and model data were removed before the comparisons were made.

In section 6.1.1 we discussed the difference of the model sea levels with the interpolation from the tide gauge data. A possible solution for the analysis would have been to remove the trends of both data sets from each of the points compared prior to analysing them. For the tide gauge data this process would have been quite simple since a clear trend between 2007 and 2016 was seen in figure 5.5. However, with the model data trend was more ambiguous. We would have gotten very different results if trend with the slope of 4.9 cm per year for the time period of 2007 – 2016 would have been removed versus having a trend of with the slope of -1.0 cm/year for time period of 2007–2013 and trend with a slope of 2.2 cm/year for 2014–2016.

Methods

In section 4.1.1 we discussed how the time interval of the tide gauge data was not always as the data file described. In some cases, the time step was varying and there weren't measurements done exactly on the hour. In those cases, we interpolated it from the other measurements done within an hour time limit from the missing measurement. This interpolation could have a little effect with the shapes of the hourly maps, but the interpolation wasn't needed much and the effect of it should be small.

The impact of changing the original height systems into EVRF 2007 using the conversion chart in 4.2 is probably on the order of few centimeters for the BSH77 datums. Celms et al. (2014, p. 52) estimates that the difference from the furthest point in Estonia to the transformation point can cause approximately 1 cm error.

The surface interpolation was done using Python programming language's SciPy package and it's interpolation method. The used method smoothed the gradient as already discussed in section 6.1.1. The residuals of the interpolated surface and the original tide gauge data were quite small. However, when there was an outlier measurement as seen in section 4.1.3 when we had erroneous Hogland values creating undulation to the surface, we saw the residual between the tide gauge data and the surface grow in the nearby stations. Whether another interpolation method or function would have worked better is difficult to say. There was some testing done with the data when choosing the interpolation method and function, mainly to see which function would have the minimal residual and reliable looking interpolation between the data points. However, interpolation for a large area with a limited amount of original data points will always have a fair amount of error.

A relating matter is the effect that missing tide gauge measurements can have to the interpolation. In the section 4.1.3 we saw an effect with undulating interpolation created by missing values between the measurements in the original tide gauge file. We then removed the Hogland tide gauge data from our interpolation and focused our efforts in removing possible outlier measurements with visually checking the grouped tide gauge time series. There can still remain some undulation of smaller amplitude that is caused by some tide gauge time series having missing values. One possible solution would be to try to prepare the data set with filling small gaps of data with interpolated values prior to making the surface interpolation. This would help with the possible undulation but would add to the uncertainty of the surface interpolation as well.

6.1.3 Did We Accomplish What We Wanted?

Answering Our Research Question

We made a surface interpolation from the tide gauge measurements in the northern parts of the Baltic Sea and then compared it to the NEMO-Nordic reanalysis product to see if the interpolated surface could be a usable approximation of the sea surface heights. The correlation between the model and the interpolated surface for the used tide gauge stations and three mid-bay points in the Bay of Bothnia the Bothnian Sea and the Gulf of Finland for the years 2007–2016 varied between 0.59 to 0.77 as seen in table 5.1. We found that the model sea levels had a jump in them in mid-winter 2013–2014 and also a different trend before and after the jump. This is probably affects the correlation as discussed in section 6.1.1. For the three mid-bay points a yearly correlation was also calculated for each year from 2007 to 2016 seen in the table 5.2. The yearly correlation yielded better results as the point in the Bay of Bothnia had correlations between 0.93–0.97, the point in the Bothnian Sea had correlations between 0.91 – 0.98 and the point in the Gulf of Finland had correlations between 0.93–0.98. These are comparable with the results of Hordoir et al. (2019) when they compared the NEMO-Nordic sea levels with nine Swedish tide gauge measurements in a time period of 1.7.2011 – 31.12.2012 and had correlations between 0.92–0.97.

There was an approximately 20 cm difference with the mean sea levels between the surface interpolation and the modelled sea levels between the years of 2007 – 2013, with interpolated surface having higher values, and approximately 28 cm difference between the years of 2014 – 2016, with modelled surface having higher values. This difference has probably something to do with how the model calculates the sea levels. We can say that they give very different sea levels but it's likely that the interpolation is more correct than the model since it follows the tide gauge measurements better.

One problem we found with the surface interpolation, was the smoothing of strong gradients across the length of the basin when the modelled sea levels showed gradients close to the shoreline. There were also some differences where we couldn't really determine whether the model or the interpolation was more correct. These included the spikes in the tide gauge data where the difference between the model and the interpolation grew as the spikes had smaller amplitudes in the modelled data. We were unable to determine whether the differences were due to overestimation in the interpolation or underestimation in the modelled sea levels. Another difference between the data sets was a variation at fairly small amplitude seen in the tide gauge interpolation but not in the modelled sea levels.

Biggest challenges in making the surface interpolation were from problems with the tide gauge data files and possible erroneous tide gauge measurements. We found the interpolation to be quite susceptible to errors and missing measurements. The inspection of the data required a fair amount of effort and was done by looking at the multiple plots of the tide gauge data. If the goal is to make the loading effect calculations operationally and automatic, the step of checking the tide gauge data computationally can become tricky. The possible situations need to be addressed are: having short periods of missing measurements, suspicious spikes or drops that are not seen in the other tide gauges nearby, the cutoff points when the spike or drop in sea level turns too suspicious, possible extreme values that are real, jumps in the mean sea level that look suspicious, situations where the exact same value is recorded for a long period of time and situation where the close by tide gauge stations show very different values or even opposite behaviour without the measurement being necessarily erroneous.

The original idea of the work was to create the surface for the entire Baltic Sea. However, the problems with data availability and the problems it caused to the interpolation explained in the sections 3.1.5 and 4.1.2 made us focus on testing the interpolation on a smaller area. The found susceptibility to errors and missing measurements makes it quite difficult to create the surface for the southern Baltic Proper with the very limited time coverage of the tide gauge data for the south-east coast of the Baltic Proper. Even if the Polish and Lithuanian tide gauge data was available for the whole period, it would still be too susceptible to errors in the data to be a good approximation of the sea levels of a very big area of the Baltic Sea. For possible uses outside of loading effect evaluation, one possibility would be to make the surface for the whole Baltic Sea and then mask off the area from the Latvian coast to southern Gotland, southern Öland, eastern Bornholm and then south to the border of German and Poland. For geodetic measurements interested in the loading effect of the sea this is not a valid method, since it would leave out a big part of the Baltic Sea mass.

Good correlations with the model sea levels indicate that the surface interpolation works to some degree in the areas where there is good enough cover of tide gauge data available but it requires careful inspection of the tide gauge data since the interpolated surface is susceptible to errors and missing data.

Future Work and Research Ideas

If we would like to test the interpolated surface for the whole Baltic Sea area, in hopes of tide gauge data availability getting better in the future, the best test period would probably be 2006–2007 since there is data available from Poland and Lithuania. However all of the tide gauge data would need to be carefully checked before making the interpolation and that would be a quite a lot of work needed to be done, either manually checking the data or making a script that would be able to recognize the problematic measurements. One interesting option could be to try to use machine learning techniques to recognize patterns of good data versus patterns of bad data.

While the surface interpolation could be a useful tool in some situation, it seems that the limitations on visual or otherwise extensive examinations of the tide gauge data prior to making the surface and the limited availability of the tide gauge data affects the usability of this interpolation in the whole Baltic Sea. Therefore it would seem that for operational use, the interpolated surface would not necessarily be the best option. However, another option might be to use the NEMO-Nordic data from CMEMS. There is an operational version of the modelled data available. As seen in this study, the model sea level is not necessarily very usable on its own. The level, however, could be adjusted using tide gauge data from a few key stations that don't have many problems with the data quality. To validate the adjusted model sea levels, other tide gauge stations not used in computing the needed adjustments for the model, could be used and maybe also altimetry data.

Finnish Geospatial Research Institute was planning to study the loading effects of the Baltic Sea mass with the use of the interpolated surfaces. This could then be compared with the upward component of the Global Navigation Satellite System's (GNSS) data from permanent GNSS network. In order to produce sea level estimates for this purpose, the adjusted model sea levels could be used for the whole Baltic Sea area, or the interpolated sea levels could be used with the exclusion of the south-east Baltic Proper and the adjusted model sea levels could be used to patch the problematic area.

6.2 Conclusions

We used tide gauge data from Copernicus Marine Environment Monitoring service and Swedish Meteorological and Hydrological Institute to make a surface interpolation of the sea levels of the Bay of Bothnia, the Bothnian Sea, the Gulf of Finland and the northern Baltic Proper. The interpolation was made hourly and for years 2007–2016. The surface was compared with NEMO-Nordic reanalysis product's hourly sea levels. The NEMO-Nordic reanalysis was also from the Marine Environment Monitoring service's data archives.

We compared maps of the hourly surface interpolation with the modelled sea levels. We plotted time ranges of point values for both sea level heights in the Bay of Bothnia, the Bothnian Sea and the Gulf of Finland. We calculated correlations of the interpolated surface and the modelled sea levels for the time period of 2007–2016 for the three mid-bay locations and also for the tide gauges sites in our study area. We also calculated yearly correlation for the three mid-bay locations. We plotted time series for the whole 2007–2016 period for the three mid-basin points of the interpolated sea level, the modelled sea levels and the difference between them.

Our research question was, "Could surface interpolated from tide gauge measurements be a usable approximation of the sea surface height in the Baltic Sea?". Our answer is yes, it could be a useful approximation. However, the availability of the tide gauge data and the need to carefully check it for possible erroneous measurements could become a problem in efforts to expand the study area to the whole of the Baltic Sea from our more limited area in the northern Baltic.

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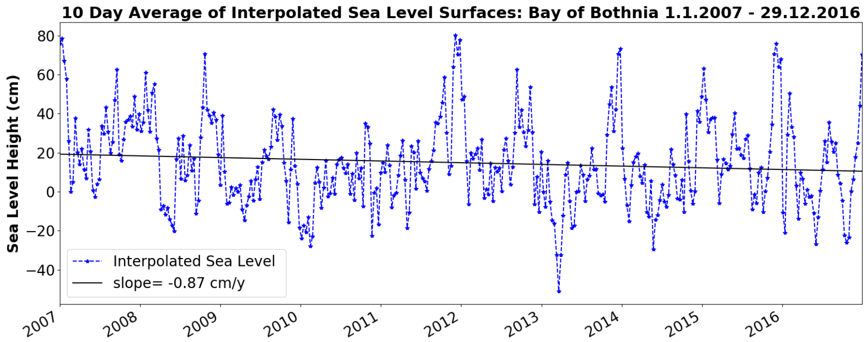
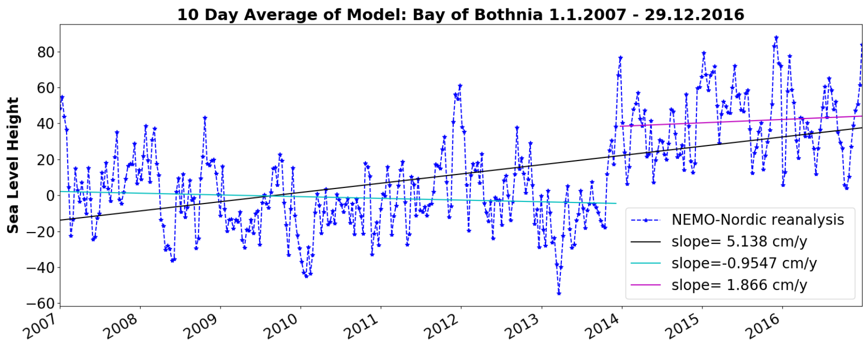
Appendices: 10 Year Time series of two points in Bay of Bothnia and Gulf of Finland



(a) Ten-day average of interpolated sea levels from tide gauge measurements in EVRF 2007 heights in centimeters. The black line is a linear fit.



(b) Ten-day average of NEMO-Nordic reanalysis sea levels in centimeters. The black line is a liner fit.

Figure 1: Ten-day averages of interpolated sea levels from tide gauge measurements and NEMO-Nordic reanalysis sea levels for a point in Bothnian Bay (lat 65.0°N, lon 23.0°E) for the period of 2007-2016.

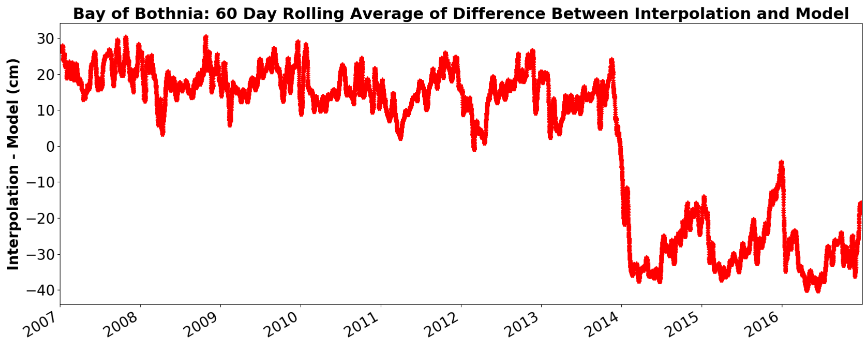
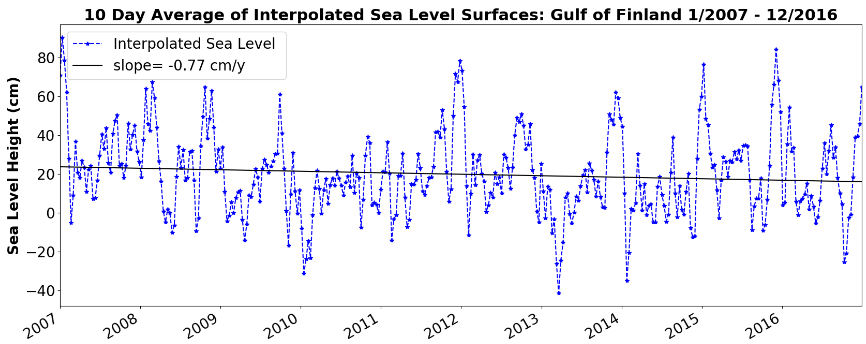
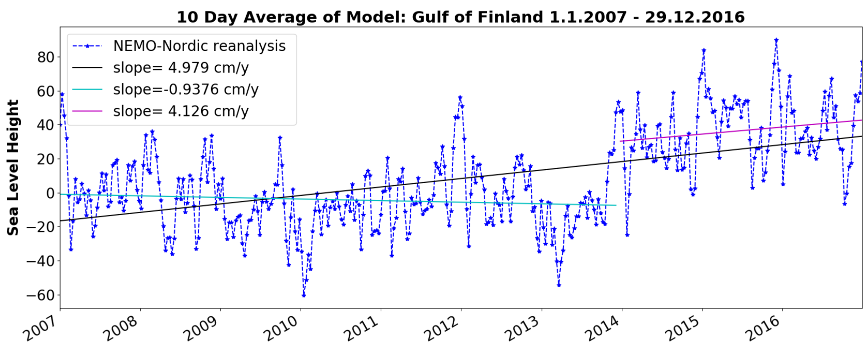


Figure 2: 60-day rolling average of difference between interpolated sea levels from tide gauge measurements and NEMO-Nordic reanalysis sea levels for a point in Bothnian Bay (lat 65.0°N, lon 23.0°E) for the period of 2007-2016.



(a) Ten-day average of interpolated sea levels from tide gauge measurements in EVRF 2007 heights in centimeters. The black line is a linear fit.



(b) Ten-day average of NEMO-Nordic reanalysis sea levels in centimeters. The black line is a liner fit.

Figure 3: Ten-day averages of interpolated sea levels from tide gauge measurements and NEMO-Nordic reanalysis sea levels for a point in the Gulf of Finland (lat 59.9°N, lon 25.0°E) for the period of 2007-2016.

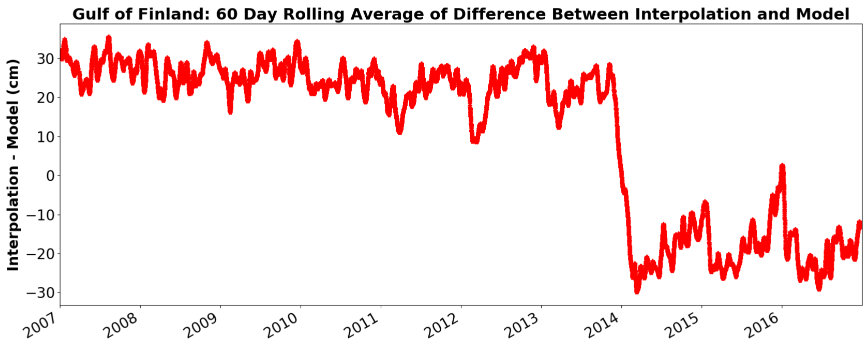


Figure 4: 60-day rolling average of difference between interpolated sea levels from tide gauge measurements and NEMO-Nordic reanalysis sea levels for a point in the Gulf of Finland (lat 59.9°N, lon 25.0°E) for a period of 2007-2016.